Building Technologies & Urban Systems Division
Energy Technologies Area
Lawrence Berkeley National Laboratory

The Cost of Decarbonization and Energy Upgrade Retrofits for US Homes

Brennan D. Less
Iain S. Walker
Núria Casquero-Modrego
Leo I. Rainer

Energy Technologies Area
August 2021

doi:10.20357/B7FP4D

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy,
Building Technologies Office, of the U.S. Department of Energy
under Contract No. DE-AC02-05CH11231.

Disclaimer

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Acknowledgment

This work would not have been possible without the generous contributions of energy upgrade project data from numerous individuals and organizations. We would like to acknowledge the contributions made by the following:

- Lawrence O. Masland and Alissa Whiteman, Massachusetts Department of Energy Resources
- Bryant Hains, Southface Institute
- Jeffrey Liang, Metropolitan Transportation Commission
- Thomas Perry of New Leaf Design, LLC, Hinesburg, Vermont for all data related to the Zero Energy Now Program in Vermont. Zero Energy Now is a program of the Building Performance Professionals Association of Vermont, administered by Energy Futures Group, Inc. of Hinesburg, VT
- Center for Energy and Environment
- EEtility and LibertyHomes
- Home Energy Analytic (www.hea.com)
- Karen Fenaughty and Janet McIlvaine, FSEC Energy Research Center at the University of Central Florida
- Sean Armstrong, Redwood Energy
- Charley Cormany, Beanstalk Energy

We would also like to acknowledge Chris Stratton, who was tasked with manual data entry for over 300 upgrade projects and whose contributions were indispensable to this work.

Executive Summary

Cost is a major barrier when upgrading homes to reduce carbon emissions required to meet DOE's climate-related goals. This report summarizes a nationwide effort to gather home energy upgrade project cost data along with household energy performance data. The goal was to develop cost benchmarks and to guide future R&D efforts aimed at cost compression and scaling of the residential upgrade market. The cost data were compiled for both total project costs and costs of individual measures. The majority of energy savings were modeled, with some models using measured site data for calibration. The database was analyzed using clustering techniques to find common energy and CO_2 reduction approaches. The individual measures were combined into archetypal solutions to determine least-cost approaches to maximizing energy and carbon savings. Several financial analyses were preformed to examine other cost metrics beyond first cost.

Project data was obtained for 1,739 projects, from 15 states and 12 energy programs, with a total of 10,512 individual measures. The database includes a wide-array of projects, ranging from single-measure HVAC upgrades to net-zero energy whole home remodels. Projects were predominantly single-family detached dwellings with wood frame construction. Most of the data was obtained from energy programs because they had recorded the necessary information and were willing to share with this study. This sample of convenience can provide broad guidance and national cost benchmarks, but lacks sufficient detail to draw more disaggregated conclusions, such as geographical trends. The majority of data contributions were obtained without compensation from sources where the required data was already in some sort of structured format. We compensated sources to enter data from individual projects into a structured data format for about 500 projects, with an average cost of about $40 per project. The database was highly skewed to lower cost, lower impact projects due to the nature of the sample of convenience. Less than 10% of projects had savings greater than 50%. The cost data for individual measures in the database are being used in other DOE efforts on residential energy use/decarbonization. This data collection effort should continue in order to provide the best-informed guidance for DOE and industry R&D, as well as deployment efforts (including policy and program planning).

Key Findings

- Energy savings estimates averaged 1,271 kWh of electricity and 12,945 kWh (440 therms) of natural gas, for a total of 8.5 kWh/ft^2. The mean CO_2 savings were 5,056 lbs. CO_2 (2.79 lbs. CO_2 /ft^2).
- Typical savings levels in most programs were insufficient to meet climate goals and decarbonize homes – future energy upgrade and decarbonization efforts must go beyond the current energy program practice reflected in the database. The best energy and decarbonization approaches saved about 70% of energy consumption and CO_2 emissions.

- When filtered to include only projects with three or more measures, the mean project cost was $19,649 ($9.28/ft^2).
- The range of reported costs for almost all measures is very large – with standard deviations about half the median value or more. This has important implications for business and homeowner risk acceptability. Measures that have better-controlled costs (i.e., less variability) are more attractive, due to reduced uncertainty. Cost control, as well as overall cost reduction, is important.
- When financed without rebates, just under half of projects in the database would have net-monthly cost savings.
- 71% of projects reported some rebates/incentives. At the project level, the mean rebate was $3,053 (median of $1,327), representing 21% of gross project costs.
- The lowest cost approaches for more than 50% energy and CO_2 savings were electrification of equipment with solar PV, combined with typical weatherization measures (e.g., cavity fill and attic insulation together with air sealing). These projects cost about $54,000 ($28/ft^2) and had median CO_2 reductions of 68%. To break even financially on a monthly basis, these projects need to reduce costs by about $20,000. Rebates and cost compression efforts are needed, even for this best-case approach.
- The highest cost approaches to saving more than 50% of energy or CO_2 were those that focused on envelope upgrades whose costs were double that of the lowest cost approach, requiring cost reductions of $70-80,000 without reaching the energy and CO_2 savings of lower cost approaches.
- Financing improves project affordability, often to the point where monthly loan costs are less than monthly energy cost savings.
- Projects saving more energy had only marginally higher net-monthly costs when financed: $9/month or $144/month for 30- and 10-year terms, respectively, at 3%. This indicates that aiming for greater savings does not come with a financial penalty. However, these higher savings projects had greater variability in net-monthly costs, indicating that aiming for greater savings is a riskier strategy.
- The levelized cost of saved energy assuming a 15-year measure life and 3% discount rate was $0.11 per kWh and $0.21 per lbs. CO_2e ($0.07 and $0.15 for a 25-year measure life).
- For financing and LCOE analyses, there was a significant range of plus or minus about a factor of three. This large range implies that, while a program that aggregates many homes together may see these very reasonable LCOE values, individual homes may not. This needs to be factored into future program planning and design, particularly when trying to reach cashflow constrained households.
- About 70 projects that electrified end-uses in states with high electricity costs increased household energy costs post-retrofit. This highlights the importance of evaluating upgrade measures in the context of local utility rates and carbon intensity of electricity.

- Both CO_2 and energy savings need to be evaluated on a state-by-state basis given the large variability in CO_2 content of electricity and the cost per unit energy of gas and electricity.

Recommendations for Future Decarbonization Cost-Related Research

Many upgrade measure costs are well-characterized by this dataset, including installation of heat pumps and gas furnaces, attic framed floor and above grade wall cavity insulation. Others are not well represented in the dataset, namely exterior insulation upgrades for walls and roofs, foundation insulation, electrical upgrades, installation of ventilation equipment and cooling equipment, and hydronic heating systems. Future cost data collection efforts should be focused on measures that are not currently well-represented, are important to decarbonization pathways, and are actionable (i.e., desirable for homeowners and profitable for contractors). The study results suggest a focus on the following:

- **Require that project data be shared in a database using a standard format** for future field projects of energy upgrades and decarbonization that DOE funds.
- **Expand the dataset to include multifamily buildings.** The dataset should be expanded to cover all residences, possibly also including manufactured homes.
- **Electrical upgrade costs,** including re-wiring, panel upgrades, and circuit upgrades for appliance replacement.
- **Soft costs,** including energy upgrade business overhead, customer acquisition, project management, work scope development, program compliance, and testing/commissioning. These are typically half the total project budget.
- **Labor, equipment, materials and other costs.** Nearly all data collected was at the total cost level, with no breakdown into these categories.
- **Appliance upgrade costs,** with a focus on replacing old gas appliances with electric ones, primarily cooking and clothes drying.
- **Mechanical ventilation equipment** is critical to avoiding IAQ problems after energy upgrades, but very few such costs were recorded.
- **Foundation insulation costs** were not as frequently reported as those for walls and attics, and the distribution of costs per treatment area were wider.
- **Battery and thermal energy storage costs.** These are still very rare in home upgrade projects and were not covered in this database.
- **Expand the sources of cost data.** Given the limitations we found in this study for obtaining complete information on home upgrades, we suggest that future cost analyses supported by DOE include outreach with state and local organizations involved in decarbonization efforts. They represent an excellent resource of motivated organizations and individuals. This outreach should use standardized approaches to

collecting and recording data, and future efforts should consider a reimbursement scheme for obtaining data as compensation for better data quality.

- **Reducing cost variability.** Develop and identify measures (and groups of measures) that are more consistent in their home-to-home costs and performance.
- **Identify specific cost-compression approaches to decarbonization with high probabilities of rapid scaling.** The electrification of equipment with solar PV, combined with typical weatherization measures approach brings significant decarbonization and energy savings within close reach. We recommend cost compression efforts in this area to help bring down wholesale equipment costs, promote effective system packages that limit the project overhead required to produce work scopes, together with demonstration projects to address industry concerns about risks associated with these efforts. Additional cost compression analyses are broadly needed for individual measures.

When designing project work scopes and programs or evaluating the benefits of home energy upgrades and decarbonization efforts, it will be essential to move beyond current performance metrics of annual site energy use, utility bills, and simple financial payback. We recommend that DOE develop and utilize analyses including the following metrics in future database development:

- **CO_2 emissions and embodied carbon.** Carbon intensity of grid electricity should be assessed with both geographic and temporal resolution. Additional effort is required to understand the embodied carbon impacts of energy upgrades and decarbonization efforts.
- **Time of use of energy.** Particularly with electrification and decarbonization, when energy is used will become as important as how much.
- **Affordability.** Focus on affordability – i.e., do not expect upgrades to pay for themselves all the time. Instead, focus on making better homes affordable.
- **Resilience.** The industry currently lacks appropriate metrics for designing or assessing the resilience of homes to power outages, natural disasters and other threats. There is also a lack of metrics to assess how a home contributes to the resilience of the grid through time-shifting energy use, demand response or storage.
- **Peak power.** Peak power needs to be considered for individual appliances, as that changes home wiring and electric service requirements. Whole home peak power is also critical, as that determines if a panel/service upgrade is required and has implications for the electricity distribution system.
- **Energy storage.** These technologies can play a critical role in alleviating grid stress and outages. They also have the potential to reduce energy costs for customers with time-of-use rate structures or with net-metering laws that provide low compensation rates for exported electricity. These represent emerging technologies that are not

represented in the database and are not part of standard practice. The industry lacks metrics that are useful and appropriate for the design and assessment of energy storage in homes.

- **Non-energy metrics.** As some of the primary drivers of home upgrade activity, future metrics should include comfort and home usability, as well as health and safety improvements (including ventilation).

Keywords

Residential, homes, retrofits, costs, energy use, electrification, decarbonization, cost stacks, financing, CO_2.

Table of Contents

Table of Figures

APPENDIX

Table of Tables

APPENDIX

1. Introduction

The cost of energy upgrades in dwellings has repeatedly been identified as one of the key barriers restricting the scaling of energy solutions and decarbonization strategies in existing homes (Chan et al., 2021; Less et al., 2021). Work early in the 2010s addressing super-insulated deep energy upgrades in existing cold climate dwellings suggested that costs could exceed $100,000 per dwelling (Holladay, 2012). In a 2014 meta-analysis of projects across the US, (Less & Walker, 2014) reported typical deep energy upgrade costs to be lower ($40,420 ± $30,358 (n=59)), which on a per square foot basis averaged $22.11 ± $17.70 per ft^2 (n=57), or about $28 in 2021 dollars. These high project costs, combined with relatively cheap retail energy costs, and a focus on cost-effectiveness, have limited the large-scale implementation of critical upgrades in the US housing stock.

The cost of energy upgrades in the US has not been consistently or centrally tracked or organized by either industry, programs or government. A methodology and practice of recording and tracking the detailed costs of energy upgrades is required for several reasons. First, the industry requires cost benchmarks against which to track the progress of changing costs, either as a result of market changes or targeted R&D to reduce measure costs. Second, the industry needs to understand where money is spent in projects as both an indicator of the magnitude of costs, but also as a reflection of the priorities in addressing decarbonization strategies. Industry and government R&D must be directed towards the measures and technologies that balance potential for cost reductions with the value provided in terms of energy, comfort or indoor air quality (IAQ). Keeping upgrades affordable is key in protecting consumers from the burden of high project costs.

This study has created a database of energy upgrade costs for the purpose of benchmarking current costs in the residential market and to identify cost compression opportunities for the decarbonization efforts required to meet climate goals. The data will also be used to update simulation and analysis tools that are used to evaluate the costs and benefits of upgrades to the housing stock, such as the NREL efficiency measure database, BEopt, ResStock, LBNL-Home Energy Saver, and to guide cost-compression in other efforts, such as the Advanced Building Construction (ABC) initiative at DOE's Building Technology Office (BTO).

The database has been developed as a sample of convenience, and it does not represent the entire residential energy upgrade market in the US. It represents the programs and projects that were willing to contribute data (both free and paid). Due to the diverse nature of the data sources in residential energy upgrades, the database was designed and structured to allow a variety of data types and levels of information to be included and analyzed. Each project in the database is represented by information in three categories:

1. Building characterization (e.g., floor area, location, climate zone, vintage, program participation).
2. Energy (e.g., pre- or post-retrofit usage, savings).
3. Upgrade measure details/costs (e.g., cost and performance details of ductless heat pump). The data base has been developed as a starting point for future DOE (and other agency) home upgrade data gathering activities.

Summaries of costs, CO_2 and energy savings are presented in this report, together with clustering analyses to develop cost stacks for different retrofitting approaches. Based on these database analyses, archetypal retrofit approaches were identified for a range of energy and CO_2 savings. The combination of clustering and archetype analyses were used to enable identification of lowest cost approaches to achieving target energy and CO_2 reductions and the measures that are the biggest contributors to project costs. The report also presents simple estimates of what is required to be cost and CO_2 neutral when electrifying homes.

Database limitations include the following:

- It does not include projects whose intent was low-cost weatherization, because the focus was on finding residential deep energy retrofit projects.
- The data gathered is a sample of convenience, so the ability to generalize the results based on geographic locations are limited.
- Not all projects provided complete information. Examples of data that was often incomplete are cost breakdowns by measure, separate reporting of soft costs, separate materials and labor, and disaggregation of heat pump installations from other electrical work.
- Many projects were not comprehensive upgrades, and typically included less than three measures.

2. Methodology

2.1 Data solicitation and Outreach

The following sections discuss how we obtained data for this project, so that future data collection efforts can be optimized based on our experience.

Project data was collected for the Deep Energy Retrofit (DER) database from two distinct sources: (1) projects documented in the publicly available research literature; and (2) projects shared by energy upgrade programs or the retrofit industry. The vast majority of projects included in the database were newly gathered from the industry and efficiency programs. The following outreach paths were used to solicit project data from the industry (subjectively sorted from most to least effective):

- Personal contacts and outreach by email
- Industry organization email blasts (e.g., *Better Buildings Residential Network*)
- Online forum posts (e.g., *Building Performance Community*)
- Residential magazine adverts in Healthy Indoors and in *Home Energy Magazine* (see Figure 1)

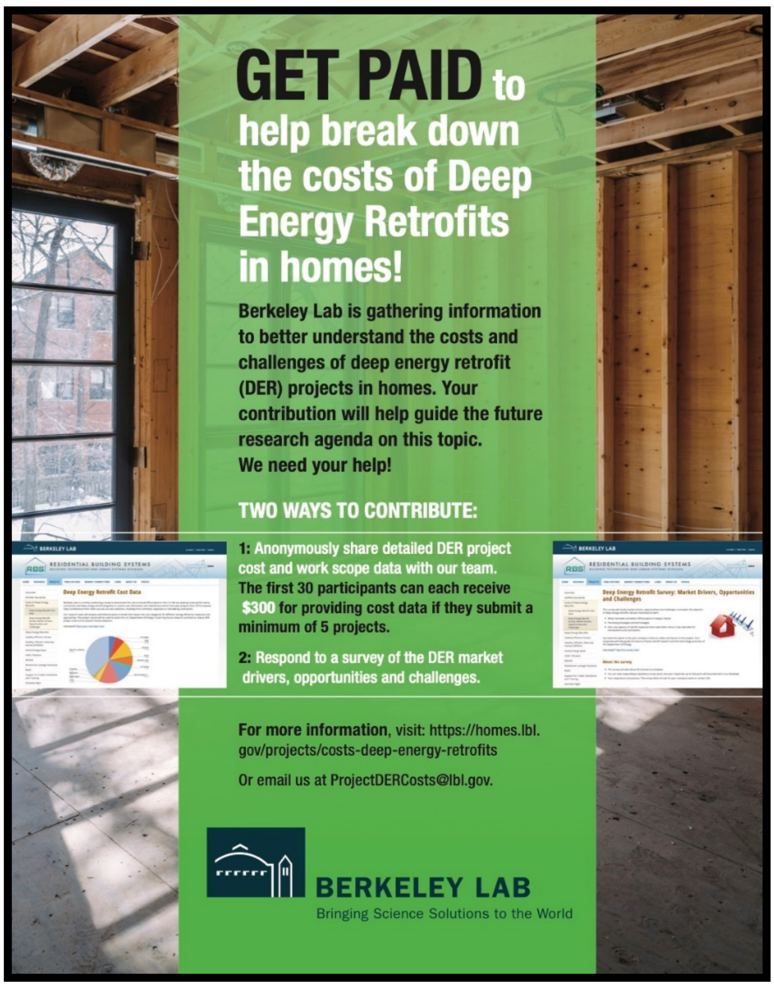
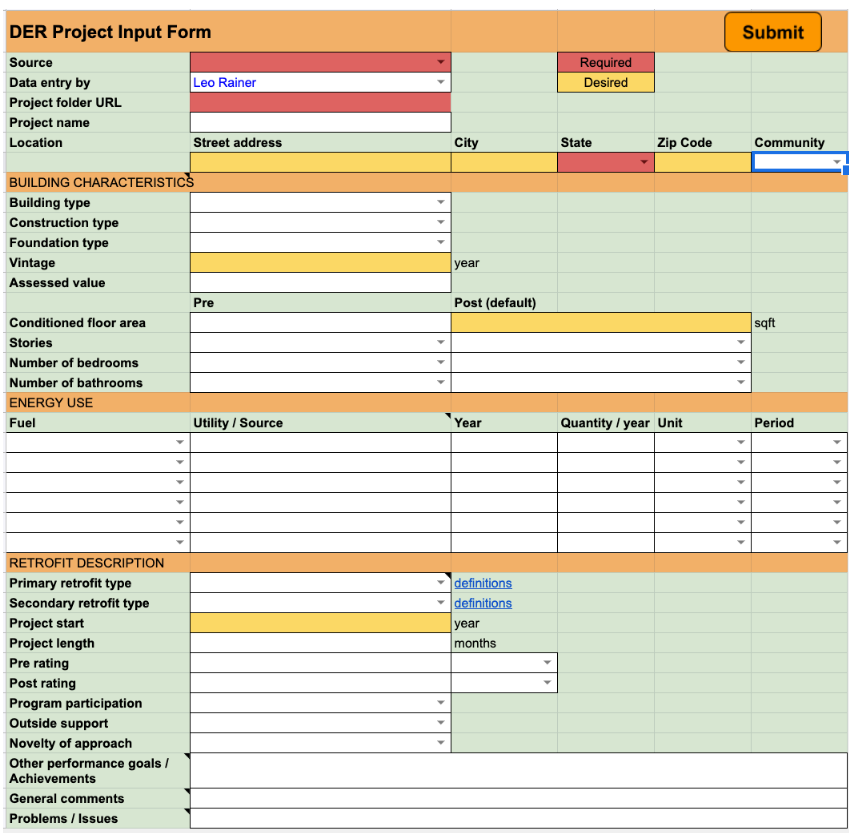


Figure 1. Magazine advertisement.

All contributors were routed through the project webpage[1] on the **homes.lbl.gov** website, where the goals of the project were briefly explained, and site visitors were prompted to respond to the energy upgrade market survey (Chan et al., 2021) and/or to contribute project data files. Project data files received as a result of these solicitations were shared either by email to the project team (most common), or through an online file upload and contributor intake page built on top of the **Residential Building Systems Group** website (least common). The website used the tool *FileUploadPro* to allow for flexible sharing of project files from users directly to the research team's cloud-based file system. Ultimately, very few submissions were received through the online data portal, and almost all contributions were received by email after substantial personal communication.

The first 30 respondents to contribute at least five projects were offered compensation of $300. Few of these compensation offers were ultimately completed. In general, project data was either shared without any compensation (representing the majority of projects), or subcontracts were required to support data sharing. Four subcontracts were executed, in exchange for data on 475 projects (27% of all projects in the database). Overall, these subcontracts worked out to $43 per project, with substantial variation ranging from roughly $17 to $200 per project. The per project costs were affected by the number of projects, the existing data format(s), and the extent of manual labor required to share project data. Those sources that had project data stored in structured databases were able to share project data at relatively low cost, while those using pdf and spreadsheet documentation required substantial manual effort to compile and share. The largest data contributions to the database were at no-cost, because all necessary project data was already contained in a simple database format.



DER Project Input Form Submit

Source			Required		
Data entry by	Leo Rainer		Desired		
Project folder URL					
Project name					
Location	Street address	City	State	Zip Code	Community
BUILDING CHARACTERISTICS					
Building type					
Construction type					
Foundation type					
Vintage		year			
Assessed value					
	Pre	Post (default)			
Conditioned floor area					sqft
Stories					
Number of bedrooms					
Number of bathrooms					
ENERGY USE					
Fuel	Utility / Source	Year	Quantity / year	Unit	Period
RETROFIT DESCRIPTION					
Primary retrofit type		definitions			
Secondary retrofit type		definitions			
Project start		year			
Project length		months			
Pre rating					
Post rating					
Program participation					
Outside support					
Novelty of approach					
Other performance goals / Achievements					
General comments					
Problems / Issues					

Figure 2. Screenshot of Project data Input Form in Google Sheets.

[1] https://homes.lbl.gov/projects/costs-deep-energy-retrofits

Project data files were received in diverse formats, including:

- Program databases
- Simulation inputs
- Project invoices/contracts
- Custom spreadsheets

Project data was entered into the database either manually via a Google Sheet input form (see Figure 2) or using scripted approaches (see further detail in Section 2.3)

2.2 Database Structure

One of the goals of this project was to develop an example database structure that could be used to gather retrofit data in future projects and provide a number of benefits including:

1. Reduce data acquisition cost
2. Keep the data format uniform
3. Make comparisons between projects easier

While we developed a schema to address these goals, due to the limited scope of this project, we only used flat files based on that schema for the data gathering and analysis.

Residential construction and residential construction firms are extremely heterogeneous, necessitating a project data entry system that is flexible in terms of detail and terminology. Cost breakdown details might vary anywhere from just a total project cost at the most generic, down to very specific details by measure, trade, materials, and labor cost. For example, a wall insulation measure might be described as “dense pack cellulose using drill and fill from the outside” or as just “blown-in”. To accommodate this anticipated variability in project data, we attempted to develop a data structure that was able to store detailed data without making it burdensome to enter simple projects.

The resulting database structure is made up of three primary tables (plus two supporting tables: Source and Performance):

- Project Summary
- Energy Use/Savings
- Energy Saving Measures

Each of these data tables are described in further detail in APPENDIX A – Database Structure.

2.3 Data Collection Entry

The project data was entered into the database using two primary methods:

- **Manual Entry:** These were individual projects, each described by reports and documents (bills, invoices, bids, etc.). See Section 2.3.1.
- **Scripted Entry:** These were organized summaries of multiple projects (usually as a database or spread sheet). See Section 2.3.2.

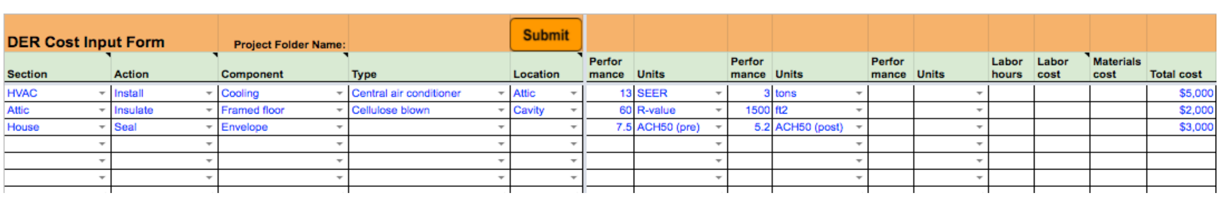
Total counts of the projects, energy and measure data obtained by manual and scripted entry are summarized in Table 1. We obtained 347 manual entry projects from 18 sources, with each source providing from 1 to 51 projects. We obtained a total of 1,394 scripted entry projects from three sources, which provided from 332 to 700 projects each. Both methods had an average of three energy use/savings entries per project (typically energy bills, modeling results and savings estimates), but the manually entered projects had more than twice as many measures per project as the scripted ones. This is due to the majority of the manual entry projects being from literature and/or research projects, which were more comprehensive than what is being done in the whole home upgrade programs that provided the scripted entries.

Table 1. Summary energy upgrade data collected.

Method	Total counts			Average Number of Entries per Project	
	Projects	Energy	Measures	Energy	Measures
Manual	347	1,081	3,704	3	11
Scripted	1,394	3,782	6,724	3	5
TOTAL	1,741	4,863	10,428	3	6

2.3.1 Manual Entry

The manual entry of the energy upgrade data required a great deal of residential construction domain knowledge to interpret and compile the project and measure data in the diverse documents provided by the various sources. In the future, this may be a major obstacle to obtaining project data unless standardized approaches to recording project information are developed and adopted in home upgrade programs. These standardized approaches may include the use of HPXML that has been developed to create a common data language for the building industry. Figure 2 shows the Project Input Form, which was used to enter the Project and Energy data fields. The red shaded fields are required – the data cannot be submitted unless all of these fields are complete. The yellow shaded fields are desired – they should be filled out, if at all possible, but the data can be submitted without them. Most fields use data validation to provide a picklist of acceptable enumerations or a range of values. Once all of the fields are filled out, the user clicks on the Submit button, which runs a script that verifies that none of the required data fields are blank, assigns a new project ID number, transfers the data to the Project and Energy tables, and clears the Project Input Form.



DER Cost Input Form — Project Folder Name: — Submit

Section	Action	Component	Type	Location	Performance	Units	Performance	Units	Performance	Units	Labor hours	Labor cost	Materials cost	Total cost
HVAC	Install	Cooling	Central air conditioner	Attic	13	SEER	3	tons						$5,000
Attic	Insulate	Framed floor	Cellulose blown	Cavity	60	R-value	1500	ft2						$2,000
House	Seal	Envelope			7.5	ACH50 (pre)	5.2	ACH50 (post)						$3,000

Figure 3. Energy upgrade Measure Input Form.

Once the project data has been submitted, the user enters all of the project measures in the Measure Input Form (see Figure 3). The Section field has a dropdown list of the 10 sections, while the Action, Component, Type, Location, and Units fields have dropdown lists that are dynamically filled based on the values of the previously entered fields. Figure 4 outlines the steps in the measure data entry process for an example single-stage heat pump installation measure (green highlighted text shows selected options from picklists). As in the Project Form, once all of the fields are filled out, the user clicks on the Submit button, which runs a script that transfers the data to the Measure table and clears the Measure Input Form.

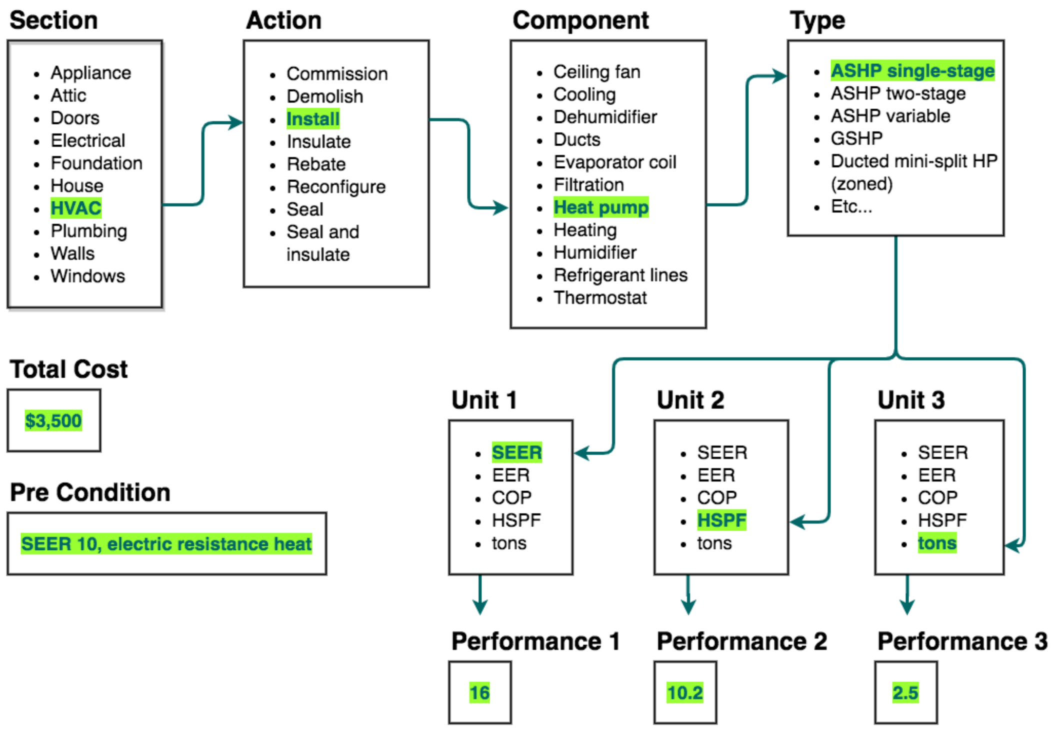


Figure 4. Example Manual Measure Data Entry Process.

2.3.2 Scripted Entry

The scripted entry data were provided to us in spreadsheet format, which made data entry possible using a set of Python computer scripts. However, each source organized their data uniquely, which required separate, customized scripts for each source. For each source, a set of data mapping rules were compiled to convert the source nomenclature and data structure to that of the energy upgrade data set. The data output of each script was three tables (project, energy, and measure) which were then integrated into the master tables generated by the manual data entry.

2.4 Adjustment for Location and Year Using RSmeans Data

The recorded project costs represent substantial diversity both geographically and in the year of project construction (from roughly 2010-2020). Both of these factors have important impacts on cost. To provide consistent, national-level benchmarks for deep retrofit measure costs, the reported prices are adjusted for inflation to 2019 USD, and are adjusted for location to be nationally representative. The 2019 reference year was selected to avoid any dollar value impacts from the COVID-19 pandemic. This method also gives us the ability to project costs forward in time, while accounting for inflation. All costs reported in this document are adjusted to be nationally representative using 2019 USD values. Once the recorded costs are normalized to 2019 national average values, then we can assess if the project costs varied by region or over-time, due to non-economic factors, such as the scope of projects, type of equipment used, methods, etc.

RSmeans cost adjustment factors were extracted from the Contractor's Pricing Guide: Residential Repair and Remodeling Costs with RSMeans Data 2020 (Lane, 2019), and these were used for both inflation and location adjustments. Location and inflation adjustment factors were sourced for the same year to ensure internal consistency in treatment of project costs. NOTE: the location factors published in the 2020 RSmeans book included mistakes, so a corrected table and set of values was provided directly by RSmeans in pdf format, which we translated to a data table.

A location adjustment factor from RSmeans was determined for each project entered in the database by identifying the RSmeans location that was geographically nearest to the project location. The recorded costs are divided by the location factor from RSmeans to produce nationally representative costs. For example, the location factor for Montgomery, AL is 0.84, meaning that costs in Montgomery are 16% less than the national average. So, a $10,000 expenditure recorded in Montgomery was adjusted to $11,904.76 (10000/0.84). The range of location adjustment factors in the RSmeans data set (n=653) are from 0.7 in Cookeville, TN up to 1.39 in Brooklyn, NY. The adjustment factors used for actual projects recorded in the database spanned nearly this same range, from 0.78 to 1.32. Adjustments to other locations are possible, by instead multiplying the recorded costs by the ratio of the desired location factor divided by the recorded location factor. The numerator is 1 when converting to nationally representative values.

Table 2. RSmeans inflation adjustment indices used to normalize recorded costs to year 2019 costs.

Year of Construction	Inflation Index [Relative to Jan 1, 2020]
2005	63.4
2006	67.8
2007	70.8
2008	75.4
2009	75.3
2010	76.7
2011	80
2012	81.4
2013	84.1
2014	85.7
2015	86.2
2016	86.7
2017	89.3
2018	93.2
2019	**97.1**
2020	100

Project location, in most cases, was represented either by the State, County, City or zip code. First, each location in the RSmeans location factor data set was attributed to a zip code based on the representative city name. The zip code was used to determine typical latitude and longitude coordinates. Second, each retrofit project was assigned latitude and longitude coordinates either directly by using the entered zip code, or by matching the project city or project county to a zip code, and then extracting the coordinates. Geospatial distance was then calculated for each project against all location factor coordinates, and the minimum distance was used to assign a location factor to each individual project. This could lead to a location factor being used from an adjacent state. Similarly, more urban or rural locations might have been imperfectly assigned based on geospatial distance, rather than by matching with market types. For projects where only, the state location was known, all RSmeans location factors in the state were averaged, and this average value was used for these projects. This approach does not account for the relative population densities represented in the

RSmeans location factors list. For example, the California state mean location factor would treat with equal weight factors representing both Los Angeles and Redding, CA. Use of these averages may over- or under-estimate actual adjusted costs.

The recorded project year was used to look up inflation adjustment index for RSmeans data, and all data were adjusted to 2019 equivalent costs. Costs for each project were multiplied by the ratio of the inflation adjustment index for year 2019 divided by the index for the recorded project year. The inflation index values for each year from 2005-2020 are listed in Table 2. For example, project costs recorded in 2016 were multiplied by 97.1 / 86.7 to adjust to 2019 dollars.

2.5 Entry Data Processing

Energy data was provided for a subset of the projects, and the energy data structure was set up to provide maximum flexibility for a variety of inputs (see Section 2.2). Based on the diverse types of energy data sources, we developed an analysis approach that translated and converted these values wherever possible to shared units and metrics. For example, if net-site energy savings were recorded along with post-retrofit net-site energy use, pre-processing was used to calculate the appropriate pre-retrofit energy use. Similarly, if percent electricity savings were recorded along with pre-retrofit electricity usage, we calculated the resulting post-retrofit electricity usage. If pre- and post-retrofit usage were reported, we calculated the energy savings and percent savings. Actual vs. modeled/estimated energy data were both recorded. These data sources are maintained separately, but most energy data shown in this report represent a merger of the Actual and Modeled energy use values. For all energy metrics/values, entries directly into the database were always preserved, rather than being over-written by the calculated values.

Site energy data entries for all energy units were converted to a common unit of MMBtu. Energy costs were calculated for most projects based on the provided site energy data and state average retail utility rates from the Energy Information Agency (EIA). Carbon dioxide equivalent (CO_2e) emissions were derived from the provided site energy data using state average emission factors for electricity and typical values for other fuel types. Details of the energy unit conversions, conversion to energy costs, and calculation of CO_2e emissions are given in APPENDIX B – Energy Unit Conversion.

2.6 Energy Upgrade Metrics

The metrics used in this study to assess deep energy retrofits fall into three main groups: CO_2 emissions, energy use and financial. The metrics used to assess projects and programs will have strong impacts on the designs and measures that are supported and implemented. This is particularly the case for fuel-switching activities, where the carbon impacts can be substantial, depending on local grid conditions. Metrics are also critical to consider when assessing how and if to make home energy use or carbon emissions a transparent element of real estate transactions.

2.6.1 CO_2 Emissions

CO2 emissions are based on the CO_2 emitted directly from on-site combustion and from the CO_2 associated with delivered electricity. Generally, CO_2 emissions are rated on an annual basis. They can be normalized by the floor area of a home to get an efficiency metric. However, having a large home emitting a lot of CO_2 but at a low rate per square foot is not going to help achieve reductions in gross CO_2 emissions.

For fossil fuel combustion, the CO_2 emissions are estimated from knowledge of combustion chemistry that is consistent and well established. For electricity, we have to account for several factors that result in several metrics being required. The main factor is that the CO_2 content of electricity is not constant and depends on the source of electricity, which varies both spatially and over-time. The sources used change seasonally and with short-term demand. The classic example is the use of gas-powered electric generation used at peak times that increases the CO_2 content of electricity on peak. Typically, these are dealt with using short or long-run marginal emission rates – although there is considerable debate over which of these (if any) is the most appropriate. Average emission rates are a good alternative, which can be directly related to the ground truth of the electricity generation mix at any point in time, whereas marginal emissions require models and predictions of what generation sources would be dispatched at any given moment based on changes in demand.

Emerging efforts by DOE and others to define appropriate carbon metrics for buildings are trending towards the use of hourly, long-run marginal emission factors from the NREL Cambium tool[2]. These are appropriate for assessing building operations at the design phase, using simulation or analysis tools. Real time marginal carbon emission rates are provided by WattTime[3] for use in operational building controls and related grid services.

Beyond CO_2 there are two other climate-related decarbonization concerns. One is the high Global Warming Potential (GWP) of many refrigerants used in heat pumps, that, if released, can have climate impacts – in which case a metric favoring lower GWP refrigerants (such as CO_2) may be appropriate. A second is the emissions of CH_4 (methane) associated with the gas distribution system. Currently this is about 2-3% of production, but due to the much higher GWP[4] of CH_4 could represent a large fraction of the global warming from using natural gas in homes. It is possible that CO_2 metrics be replaced with GWP metrics that would include the impact of CH_4 leakage.

2.6.2 Site Energy Use

Energy upgrade metrics for energy use are typically annual energy use and energy use normalized by floor area. However, as we move towards net-zero energy (and carbon) goals, there is more emphasis being placed on absolute energy use rather than normalized by square forage of a home. This is because the goal is related to energy use rather than how efficiently energy is used. Note that this also aligns with *DOE Home Energy Score* tool which is used for existing home projects and retrofits. Similar to CO_2, having large homes that use a lot of energy, even if their floor area normalized energy is low, are not getting us to low or zero energy targets. Other energy metrics are related to reductions in energy after home upgrades. As with overall energy use, the metrics can be absolute as well as normalized – typically by floor area. In addition, a valuable metric in assessing homes is the fractional energy saved. This allows a reasonable balance between small and large homes and high and low energy using households when assessing energy upgrades. Energy performance metrics should be based on the

[2] https://cambium.nrel.gov/
[3] https://watttime.org
[4] CH_4 has more than 80 times the global warming potential of CO_2 over its first 20 years of release.

ubiquitous actual energy consumption data that is available, increasingly with excellent time resolution.

Site energy use assessments must be expanded to include time-of-use and peak demand considerations, which have important carbon, energy cost and grid stability implications. Currently, there are very few, if any, examples of time-of-use energy metrics that assess or grade projects on when they use energy and how much. One notable exception is the Time Dependent Valuation energy metric used by the California Energy Commission.

2.6.3 Financial

Several financial metrics were used in this project:

- Energy cost is the simplest financial metric used in home performance assessment. As with energy and carbon, various normalizations are possible to make energy costs comparable across groups of homes. Typically, total annual energy cost and cost per ft^2 are used.
- Simple payback, where the energy bill savings and measure costs are used to determine how long it takes to pay off the investment in home upgrades. This has the advantage of simplicity, but may not align with how lending institutions or home owners assess finances.
- Net-monthly cost of ownership based on household cashflow. Typically, this metric compares energy bills to the monthly cost of financing home energy upgrades.
- Levelized cost of saved energy based on normalized costs per kWh of savings, lbs. CO_2 savings, or initial cost. Measure life and discount rates are used to support comparisons across a variety of measure types and programs.

Affordability is a new metric being used by some industry pioneers (such as *BlocPower* and *Sealed)* and is related to net-monthly cost of ownership. The target is to make a homeowner comfortable with a given monthly expense in return for living in a better performing home. This may be a way to broaden financial analysis approaches to reach larger market segments.

2.6.4 New Metrics for Home Energy Upgrade / Decarbonization

Several additional metrics were not used directly in this study, but should be considered in future cost and energy analyses related to home upgrades/decarbonization.

2.6.4.1 Embodied Energy

Generally, it is very difficult to determine the embodied energy involved in home upgrades and embodied energy metrics are not used. Primarily this would be in the manufacture of physical things, such as heat pumps or insulation. Including the embodied energy (and associated CO_2) is something that requires additional effort in the future. Many products provide Environmental Product Declaration (EPD) sheets, which include standardized assessments of the embodied energy and carbon associated with the products. Data from these EPD documents needs to be assembled in a structured database, which can then be dispatched consistently within energy modeling and design tools. Such databases do exist currently that assemble publicly available EPDs (e.g., Embodied Carbon in Construction

Calculator (EC3)[5]), but they are not integrated with design processes or assessment tools in residential construction. Extending this analysis beyond manufactured products and into upgrade activities themselves (e.g., jobsite travel) is even more difficult. More work is needed to assess the relative impacts of operational carbon savings versus carbon emissions associated with upgrade activities. The net-effects will depend greatly on materials and methods used, along with the analysis assumptions, period of analysis, etc.

2.6.4.2 Health, Resilience and Comfort

In feedback from industry surveys (e.g., (Chan et al., 2021)) and other resources, it is becoming clear that decisions regarding home energy upgrades are inspired by a wide range of issues not captured in current evaluation metrics that focus purely on simple financial analyses. Health and safety impacts resonate with home owners and are an important part of the homeowner decision-making process. Metrics that are currently being used or considered include IAQ-based health impacts, such as reduced risk of respiratory-related health problems or improved kitchen safety. There is a considerable literature on the impact of gas cooking on health – particularly for children. There are efforts under way to use health as a reason to upgrade from gas to induction cooking, including proposed changes to California building codes that would have more stringent code compliance paths for homes cooking with gas. From a safety perspective, removing gas from a home removes concerns about carbon monoxide poisoning, fire safety is improved because there are no naked flames, risk of burns is lower for induction due to much lower cooktop surfaces, and, at a larger scale reduced risk of gas explosions and post-earthquake fires. Accounting for all these safety effects may be impractical from a metrics development point of view, yet they may be important factors in encouraging homeowners to decarbonize.

While comfort and utility (i.e., the ability to use space fully due to conditioning improvements), add to home value, and the "feel-good" factor of living more sustainably, it is far from clear how to capture these effects in a numerical way that could be used to assess home energy upgrades. Given that they are essential and can be dominant in the decision-making process, some efforts here are warranted.

Resilience metrics currently do not exist. They would have to find a way to account for comfort, health and other effects related to how well a home performs when faced with challenges, such as heat waves, cold spells, energy infrastructure failures, wildfires, flooding, etc. These challenges are diverse and represent a significant challenge in developing metrics to account for them individually or bundled together. Developing appropriate metrics in this area is a topic for future work.

2.6.4.3 Peak Power

Peak power needs to be considered for both individual appliances (that changes home wiring and electric service requirements) and the whole home (that determines if a panel/service upgrade is required and has implications for the electricity distribution system). For individual end uses their peak power (kW) is an appropriate metric. Whole house metrics are more difficult as they must account for diversity, however, methods to address this are readily available, for example, current electric codes already allow for assumed diversity when sizing circuits and panels. Some practitioners have developed extensive guidance on how to limit peak power requirements that show how this metric can be effectively utilized (Armstrong et al., 2021). It is likely that these existing methods will need to be updated as we increasingly focus on managing peak power for all-electric homes. There may need to

[5] https://www.buildingtransparency.org/

be metrics developed that allow for rating of smart panels and switches that allow multiple end-uses to share electric circuits. Home charging of EVs is an additional load that needs to be accounted for in peak power analyses. In addition, vehicle-to-grid technologies are emerging that allow vehicle batteries (typically many times the kWh capacity of home battery solutions) to discharge energy to the home. This feature is critical in case of power outages, or to serve as a means to manage and separate when energy is delivered to the home vs. when it is used in the home. This can have substantial energy cost and grid benefits.

2.6.4.4 Time of Use of Energy

Knowing not just home much energy, but when it is used are vital for successful large-scale home electrification for good integration into the grid and to manage billing costs, that may include demand and time of use charges. Currently, there are very few, if any, examples of time-of-use energy metrics that assess or grade projects on when they use energy and how much. One notable exception is the Time Dependent Valuation (TDV) energy metric used by the *California Energy Commission*.

2.6.4.5 One Site Generation and Storage

Metrics are needed for on-site power generation capability, normally Solar PV. Existing metrics for PV are peak power output (kW) and annual energy (kWh) (that includes local solar availability, shading and installation geometry).

Metrics are needed for energy storage to account for changing cost per kWh and CO_2 content of electricity with time. Simple metrics exist, such as the capacity of a battery or thermal storage device or its maximum power capability (for both charging and discharging). It is likely that we need integrated metrics that combine energy storage directly into CO_2 emissions and operating costs. There is a need for related guidelines on how much energy storage is needed for a given thermal/electric system. Example metrics would be storage capacity as a percentage of annual loads, or percentage of peak power consumption. In addition to storage, other approaches that can time-shift energy use provide energy flexibility. For example, smart ventilation systems that shift ventilation loads in time or behavior changes that can shift laundry and dishwashing to off-peak times. Substantial future work is required to develop useful and appropriate metrics in this space.

2.6.4.6 Non-Energy-Related Concerns

In feedback from industry surveys (e.g., (Chan et al., 2021)) and other resources, it is becoming clear that decisions regarding home energy upgrades are inspired by a wide range of issues not captured in current evaluation metrics, and therefore, some metrics to address this are required. Topics requiring metrics include: health and safety impacts, comfort, utility (i.e., the ability to use space fully due to conditioning improvements), added home value, and the “feel-good” factor of living more sustainably. It is far from clear how to capture these effects in a numerical way that could be used to assess home energy upgrades but, given that they are essential and can be dominant in the decision-making process, some efforts here are warranted.

2.7 Regression Modeling with Machine Learning

Regression modeling was performed for two purposes: (1) to predict cost (or energy savings); and (2) to determine how important each variable was in the prediction. Regressions were developed for each retrofit measure (e.g., install heat pump), with a combination of project- and measure-based predictor variables. Similar regression modeling was performed to predict the net-site energy and carbon percent savings of an entire project, given the costs recorded in each unique combination of Section-Action-Component. All modeling was implemented using the caret package[6] in *R*, which is designed to provide a consistent format for implementing machine learning models. This work leveraged the caret package's tools for cross-validation, recursive feature elimination and variable importance estimation. Several regression techniques were investigated and random forest regression was found to have much lower cross-validated prediction errors than other approaches. In the rest of this report, we present the results of the random forest regressions. Details of the regression modeling can be found in APPENDIX C – Regression Modeling.

2.8 Levelized Cost of Saved Energy

The levelized cost of saved energy (LCOE) is a type of analysis commonly used to assess the financial performance of demand-side efficiency programs, including whole house retrofits, as they compare to other supply-side energy sources (Billingsley et al., 2014; Goldman et al., 2020).

The measure life and discount rates are important factors in determining the outcomes of the analysis. For a given cost and savings, the LCOE are reduced when using longer measure life and lower discount rate values. A 6% discount rate is commonly used as a proxy for the cost of capital for typical investor-owned utilities (Goldman et al., 2020). But others have justified lower discount rates of 1-3% for use in environmental assessments of carbon emissions[7]. Our analysis preferentially uses the 3% discount rate. The measure life is also difficult to characterize, particularly in programs and projects that include a wide-ranging mix of measures and materials. Billingsley et al. discuss this issue at length, and they published reported measure/program lifetimes for different program types, including whole home retrofits. The interquartile range for whole home energy upgrade program measure life spanned from 10-25 years across 16 programs examined, with a median just above 15-years. In Appendix Table C-3 of (Billingsley et al., 2014), their chosen typical measure lifetimes are listed for all residential measures, with electric measure lifetimes ranging from 10-20 years, and gas measure lifetimes ranging from 15-25 years. Billingsley took whole home retrofit values to be 15 and 21 years for electrical and gas measures, respectively. Based on this analysis, we show LCOE results for 15-year (typical estimate) and 25-year (high estimate) assumed measure lifetimes.

2.9 Financing and Cash Flow

We performed financing/cash-flow calculations for the purpose of representing the cost-effectiveness of the projects entered in the database. Annual energy cost savings were divided by 12 to get monthly cost savings. Monthly loan costs were calculated using standard loan repayment algorithms[8]. The net-cost was the monthly loan cost minus the monthly energy cost savings. We used a variety of financing terms, including 10-, 20- and 30-year loan periods, paired with 0%, 3% and 8% interest rates. These financing terms were intended to represent the typical ranges for home upgrade financing, including those for mortgages and for Property Assessed Clean Energy (PACE) loan programs[9].

[6] https://topepo.github.io/caret/

[7] https://www.carbonbrief.org/qa-social-cost-carbon

[8] (x/((((1+(y/12))^(12*z)-1)/((y/12)*(1+(y/12))^(12*z))))). x = loan principle $; y = fractional interest rate; z = loan term, years

[9] All information related to PACE program loan terms and fees (as of May 2018) is sourced from: (Bay Area Renewable Energy Network, 2018)

Note, the loan cost estimates in this report do not include mortgage interest deductions from Federal or State income taxes (which would increase net-cash flow), and they also do not include loan closing costs (e.g., application costs, title, fees, etc.) or program administration costs (which would decrease net-cash flows). For example, program administration fees for PACE programs are typically in the range of 5-6% of the funded amount, with relatively small title and application fees of roughly $100 each.

Pay-As-You-Save (PAYS) programs are another increasingly common means of financing home energy upgrades and electrification work, but these programs do not technically issue loans to customers. Yet, the repayment structure is similar in that there is an anticipated period over which capital costs are recovered (typically 12-years), the recovery occurs at the rate that energy costs are reduced in the home, and up-front program costs are on the order of 3%. Our analysis of PAYS programs includes 12-year repayment, 0% interest rate, with a 3% increase added to the loan principle (i.e., the project cost times 1.03).

2.10 Present Value of Savings and Required Cost Compression

For projects that reported energy savings or cost savings, we can use those values to estimate the total gross project cost that could be cost-effectively supported by the current savings. We refer to this as the "*supportable project cost*". We can then compare these supportable project costs against the actual project costs recorded in the database. The difference between the two (actual minus supportable) is the "*required cost compression*" in order for the projects (as currently designed and implemented) to be cost-neutral based on a given analysis period and discount rate. We frame these present value calculations as loans, with certain repayment periods and interest rates. Note: these calculations ignore all other sources of upgrade project value other than utility bill savings. They do not include valuation of improved health, comfort, durability, etc. These non-energy benefits have been posited as being substantial in dollar terms (Zhu et al., 2020) as well as societal benefits of improved health and reduced mortality (IEA, 2014).

For each project, we calculated:

- The monthly energy cost savings (n=1,212). These are strongly dependent on utility rate assumptions. Changes to utility rates, such as increased natural gas prices, would substantially alter the monthly savings and supportable project costs.
- The present value of these monthly savings (e.g., the project costs supported by energy cost savings). We use 3% and 8% discount rates (i.e., loan interest rates) and terms of 10-, 20- and 30-years. See the formula for calculating the present value of an annuity below.
- The difference between the recorded actual project cost and the supported project costs is the required cost compression for the project to be cost-effective/cost-neutral.

The process for deriving the required cost compression for each project is illustrated in Figure 5 and Equation 1.

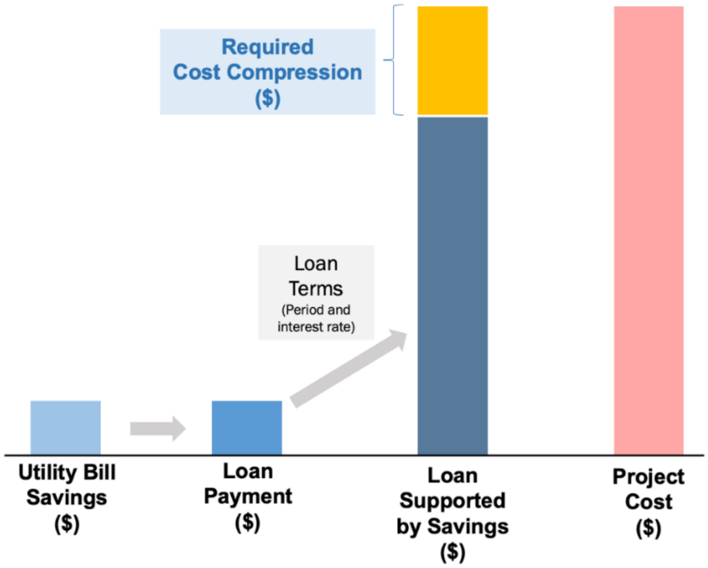


Figure 5. Illustration of the process for deriving the supportable project cost and the required cost compression for each project.

Equation 1. Loan amount.

$$PV = \frac{PMT}{i}\left[1 - \frac{1}{(1+i)^n}\right]$$

PV = Loan amount (i.e., present value), $

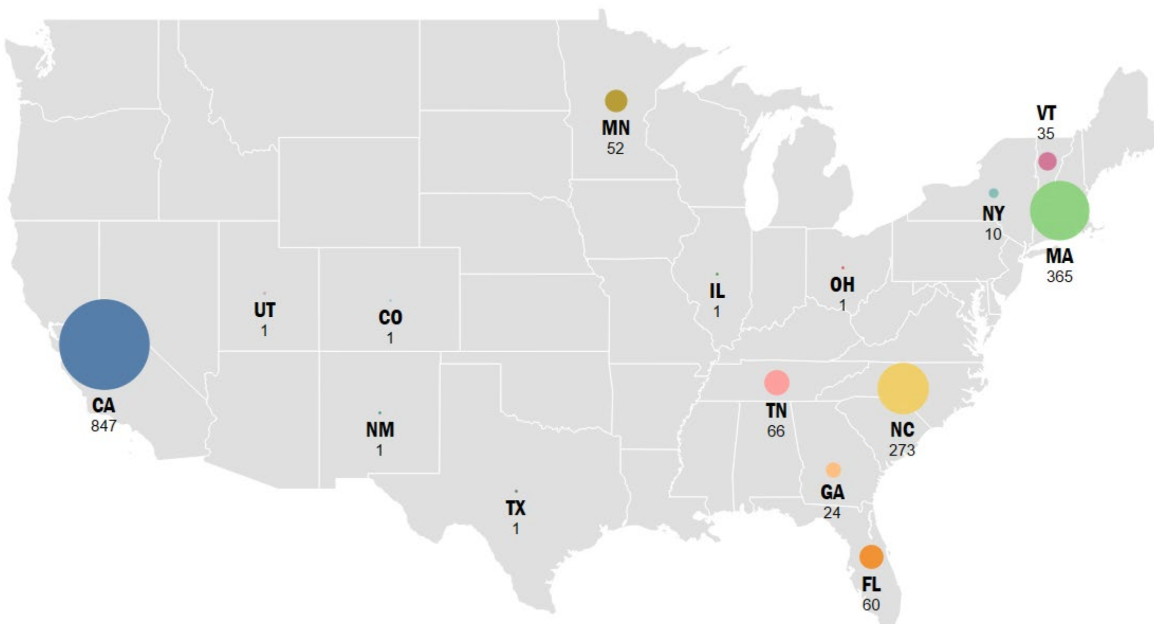
PMT = Monthly payment, $

i = Interest rate per month in decimal form (interest rate percentage divided by 12)

n = Number of months (term of the loan in months)

3. Database Summary

All 1,739 projects recorded in the database are indicated by state in Figure 6, along with overall summary statistics for the number of programs, projects, and retrofit measures, plus the total square footage and total expenditures represented in the dataset. Project and measure costs reported in this document do not include any incentives (i.e., gross project costs) and therefore can illustrate where incentives might make a big difference, e.g., through eligibility for Federal tax credits (that almost all the work in these cost stacks would be eligible for) or rebates (e.g., for heat pumps for reducing the cost of electrification and for home insulation projects).



12 Programs   1,739 Projects   10,512 Measures   3,294,946 ft² $24,689,213

Figure 6. Map of project locations and overall summary statistics.

The median project cost was $8,740 (mean of $14,429), with a median of $4.95/ft^2. But many projects included very few measures. The median number of measures in a project was 3 (mean of 3.6). 447 projects had only one costed measure, while 355 had two costed measures. If projects are limited to those with three or more measures (n=923), the median project cost increased to $10,802 (mean of $19,649). The median measure cost overall was $2,761 (mean of $5,285). See Section 7.1 for more details on project costs. 71% of projects reported receiving incentives to partly fund the energy upgrade work, with a median incentive of $1,327 (mean of $3,053; n=1,218), representing 21% of gross project costs. Incentives were highly variable depending on the program the project participated in (see Section 7.1). In total, the 1,739 projects recorded a combined annual energy cost savings of $835,622 (n=1,228), with annual net-site energy savings totaling 13,111,825 kWh (n=1,185) and an annual reduction of 5,758,242 lbs. of CO_2e emissions (n=1,139). The median percent savings across all projects reporting energy use data was 28-33%, depending on the metric used (see Section 8 for more information on energy performance).

The 6,165 retrofit measures that included cost data and were not incentives are subdivided by Section into counts in Figure 7 and into total recorded costs in Figure 8. The median installed costs and interquartile ranges are shown for the most frequently installed measures in Figure 9. The most measures were recorded in the HVAC, followed by House and Attic Sections, while by far the greatest expenditures were recorded in the HVAC section ($14.2 million). The next greatest expenditures were recorded in the Attic, House and Electrical sections. When all building envelope-related Sections are added together, they total 1,742 measures compared with 2,298 HVAC measures. When envelope-related costs are summed, they total $5.3 million compared with $14.2 million for the HVAC section. These results demonstrate the dominance of HVAC work in current energy upgrade programs and projects, particularly in terms of expenditures. The House section includes building envelope air sealing and also rebates/incentives, which explains the prevalence of measures. The Electrical section includes both lighting upgrades and PV installation. Almost all project cost data submitted fell under the total cost category, with effectively no detail provided on labor/material breakdowns. This is an important limitation when considering where best to put cost reduction efforts.

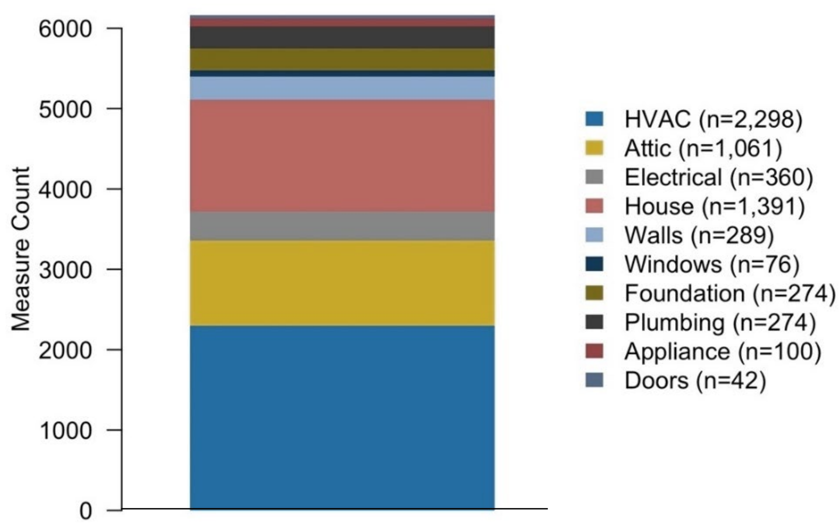


Figure 7. Count of recorded measures by section.

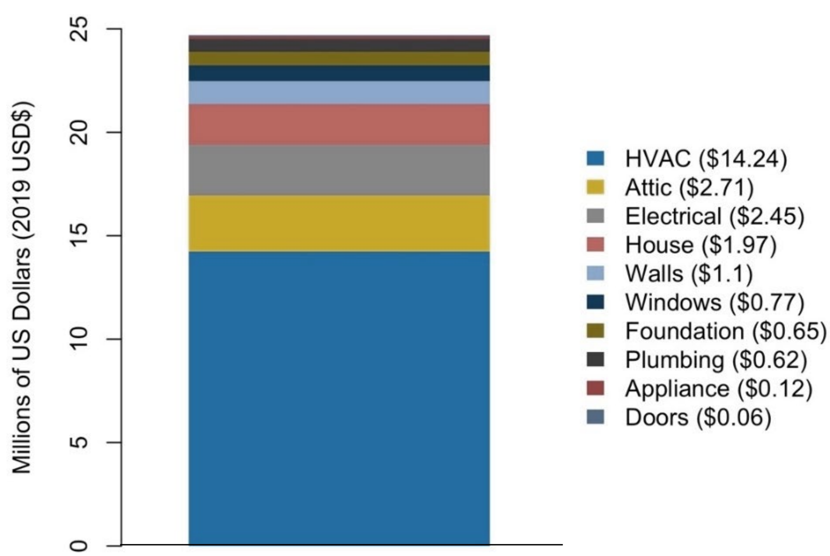


Figure 8. Total recorded expenditures by section.

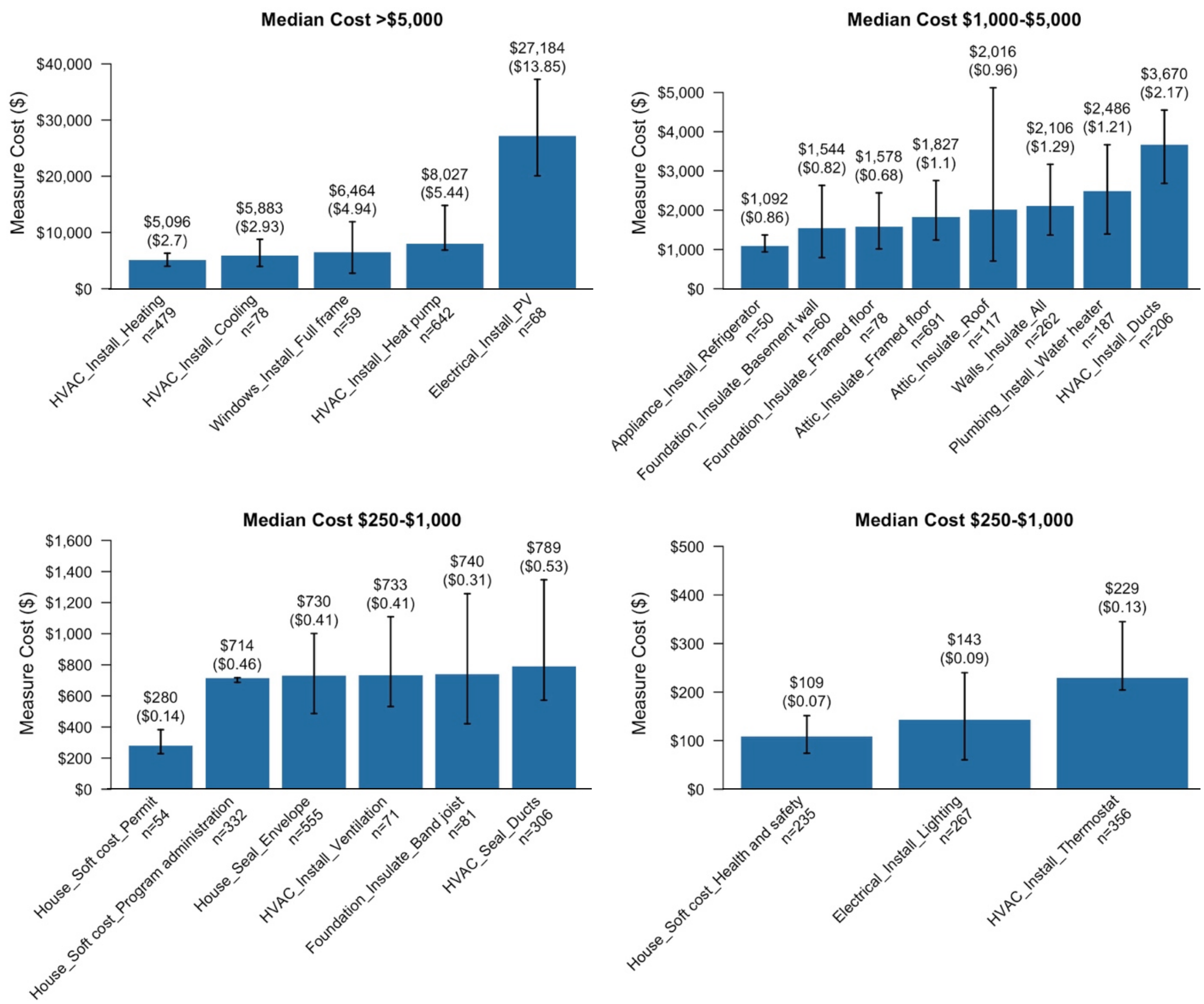


Figure 9. Most frequently installed upgrade measures, median installed costs and interquartile ranges.

4. Clustering Measure Packages

To better understand the types of retrofit projects gathered in the energy upgrade data, we applied clustering techniques using the measure costs for each individual project. Clustering is an unsupervised machine learning technique used to identify similar groups of objects in a dataset. A total of six distinct clusters were developed, ranging in size from 14 to 857 projects. Clustering was performed using only cost data, and it did not include project meta-data (e.g., location, vintage, etc.), measure performance (e.g., heat pump efficiency or R-value) or energy performance.

We first reduced the dimensionality of the 165 unique Section/Action/Component measure combinations to a set of eleven cost categories using the mapping shown in Table 3. An asterisk (*) indicates that all enumerations are mapped unless directly specified elsewhere. For example, all measures with a section enumeration of Electrical are mapped to the Electrical Category except for Electrical / Install / Lighting, which is mapped to the Lighting Category, and Electrical / Install / PV, which is mapped to the PV Category. This mapping also combines some sections, such as Doors and Windows, combines all sealing and insulation work together, and moves Rebate and Soft costs to their own categories so that just hard costs would be used for the cluster analysis.

Table 3. Mapping of measures to clustering cost categories.

Category	Section	Action	Component
Appliance	Appliance	*	*
DHW	Plumbing	*	*
	House	Install	Solar thermal
	House	Install	Water heater
Doors and Windows	Doors	*	*
	Windows	*	*
House	House	*	*
	*	Paint	*
	*	Demolish and dispose	*
	*	*	Interior finish
	*	*	Exterior finish
Electrical	Electrical	*	*
HVAC	HVAC	*	*
	House	*	Ducts
Lighting	Electrical	Install	Lighting
PV	Electrical	Install	PV
Rebate	*	Rebate	All
Seal and Insulate	Attic	*	*
	Foundation	*	*
	Walls	*	*
	House	Install	Weather stripping
	House	Insulate	*
	House	Seal	*
	House	*	Envelope
Soft Cost	House	Remediate	*
	House	Soft cost	*
	House	Test	*

We reviewed the costs in each category and dropped three projects due to them having a measure cost that could significantly bias the results: Project 1055 had $150K of House section costs; project

1079 had $141K of House section costs; and project 1311 had $204K of PV costs. All of these were over nine times the interquartile range above the upper quartile of the other projects. Once the data had been cleaned, we applied the k-means partitional clustering technique using the Python scikit-learn package[10]. Because all category values were in the same unit (dollars), no data transformations (e.g., centering) were required before running the cluster analysis. The number of clusters must be selected by the user in such an analysis and there is some subjectivity involved. To determine the number of clusters to use, we examined the sum of squared error (SSE) resulting from k-means runs including anywhere from two to ten clusters (see Figure 10). The SSE is a measure of how much variability is included in each distinct cluster, and this value always goes down as cluster number is increased. Typically, this should result in a curve with a pronounced "elbow", which is the point where adding clusters becomes less effective at reducing the SSE. In this case, the analysis did not result in a conclusive optimum number of clusters. We reviewed the five, six, and seven cluster results with respect to category costs and project characteristics that made sense from a building retrofit perspective, and we settled on six clusters, as a set, that worked well and provided good insights into the cluster characteristics.

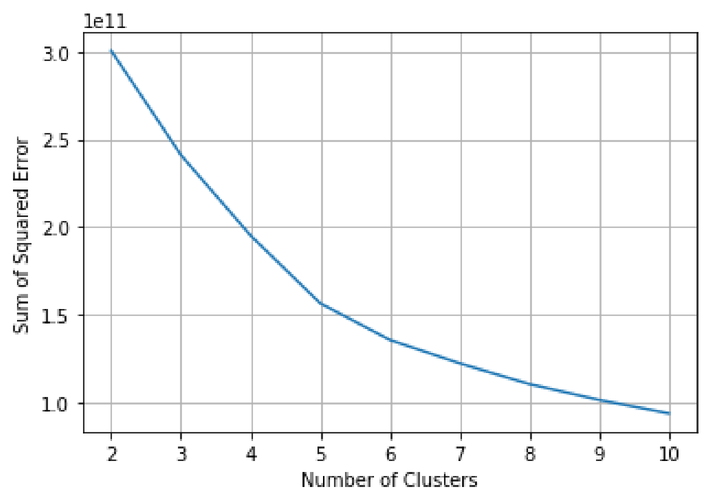


Figure 10. Clustering Sum of Squared Error (SSE).

Table 4. Cluster label descriptions.

Label	Description
Basic	Low-cost, basic projects with mostly envelope and limited HVAC work
HVAC	HVAC projects with standard equipment (~1/2 heat pumps), including some envelope work
Advanced HVAC	Advanced, higher-cost HVAC projects (>2/3 heat pumps), including some envelope work
Large Home Geothermal	HVAC-focused projects in large homes with geothermal heat pumps (90%) and some envelope and PV work
Superinsulation	Comprehensive deep retrofits focused on aggressive envelope upgrades (e.g., exterior wall insulation, triple pane windows, etc.) with some gas equipment and little or no PV
Electrification with PV	Equipment electrification projects that include moderate envelope upgrades and PV in all cases

Based on this expert review, each cluster has been assigned a short, human-interpretable name that represents some of its primary characteristics (see Table 4). Although the clustering was done using

[10] https://scikit-learn.org/stable/

just measure costs, the other characteristics of the projects in each cluster provide useful information for evaluating what each cluster represents (e.g., project duration, total cost, number of measures, etc. See Table 6). The clusters are described in order of total net-site energy savings, from lowest to highest. Further detail is provided on the most frequently installed measures in each cluster in Table 5, with median measure costs listed for those that were included in at least 25% of projects within each cluster. The median measure category cost in each cluster is shown in Table 7, and Table 8 shows the fraction of projects of in each cluster that recorded costs in each category. In both tables, values are highlighted in bold text when more than 25% of projects included a cost in the category. Each cluster is described below, along with pictures characterizing common features within each set of projects.

Table 5. Measure frequency and median costs for each cluster. Limited to measures reported in >25% of projects.

Cluster	Section / Action / Component	Fraction of Projects	Median Measure Cost			
			Measure Cost $	$ per Floor Area	$ per Treatment Area	$ per ton
Basic	Attic/Insulate/Framed floor	59%	$ 1,903	$ 1.14	$ 1.67	---
	House/Seal/Envelope	38%	$ 773	$ 0.43	---	---
	Walls/Insulate/All	28%	$ 2,106	$ 1.29	$ 2.11	
HVAC	HVAC/Install/Heat pump	55%	$ 7,695	$ 4.97	---	$ 2,748
	HVAC/Install/Heating	42%	$ 5,543	$ 2.93	---	$ 1,053
	HVAC/Install/Thermostat	39%	$ 229	$ 0.13	---	---
	House/Seal/Envelope	38%	$ 654	$ 0.40	---	---
	Electrical/Install/Lighting	34%	$ 153	$ 0.10	---	---
	HVAC/Seal/Ducts	34%	$ 789	$ 0.55	---	---
	Attic/Insulate/Framed floor	27%	$ 1,546	$ 1.00	$ 1.97	---
Advanced HVAC	HVAC/Install/Heat pump	73%	$ 24,419	$ 9.87	---	$ 6,008
	HVAC/Install/Heating	32%	$ 8,794	$ 4.21	---	$ 1,145
	HVAC/Install/Cooling	26%	$ 8,576	$ 3.55	---	$ 2,633
Large Home Geothermal	HVAC/Install/Heat pump	93%	$ 71,435	$ 17.09	---	$ 18,548
	Plumbing/Install/Water heater	50%	$ 4,191	$ 1.24	---	---
	Attic/Insulate/Roof	29%	$ 2,787	$ 0.96	$ 1.88	---
	Electrical/Install/Lighting	29%	$ 37,634	$ 3.91	---	---
	HVAC/Install/Thermostat	29%	$ 3,064	$ 0.28	---	---
	House/Seal/Envelope	29%	$ 771	$ 0.24	---	---
	Plumbing/Install/Low-flow fixtures	29%	$ 2,868	$ 0.34	---	---
Superinsulation	House/Seal/Envelope	80%	$ 4,811	$ 2.67	---	---
	Walls/Insulate/All	80%	$ 12,834	$ 5.88	$ 4.08	---
	Attic/Insulate/Framed floor	53%	$ 5,447	$ 3.11	$ 5.86	---
	HVAC/Install/Ventilation	53%	$ 1,245	$ 0.61	---	---
	Foundation/Insulate/Basement wall	47%	$ 8,890	$ 5.40	$ 14.39	---
	Attic/All/All	40%	$ 11,247	$ 7.11	---	---
	Walls/Install/Exterior finishes	40%	$ 34,669	$ 11.75	---	---
	Windows/Install/Full frame	40%	$ 11,189	$ 5.49	---	---
	Attic/Insulate/Roof	33%	$ 20,361	$ 4.29	$ 22.72	---
	Doors/Install/All	33%	$ 3,508	$ 2.51	---	---
Electrification with PV	Electrical/Install/PV	100%	$ 28,827	$ 15.17	---	---
	HVAC/Install/Heat pump	95%	$ 11,567	$ 5.92	---	$ 4,681
	House/Seal/Envelope	77%	$ 1,240	$ 0.62	---	---
	Attic/Insulate/Framed floor	56%	$ 2,023	$ 0.89	$ 3.28	---
	Foundation/Insulate/Basement wall	51%	$ 1,481	$ 0.74	$ 4.46	---
	Foundation/Insulate/Band joist	49%	$ 688	$ 0.29	$ 6.10	---
	Plumbing/Install/Water heater	49%	$ 2,503	$ 1.37	---	---
	Walls/Insulate/All	47%	$ 1,478	$ 0.47	$ 4.67	---
	Attic/Insulate/Roof	40%	$ 2,448	$ 1.27	$ 8.25	---

Basic and HVAC: These first two clusters contain almost 90% of the projects in the study. They represent typical home performance projects or HVAC equipment upgrades that are not quite "deep" retrofits. They have low costs (< $20K) and focused primarily on the HVAC and Seal and Insulate categories. They are simple projects (median of 2-3 measures per project) that were completed in a short time (median of one month). The principal difference between them, other than cost, is that the Basic cluster focused on sealing/insulation and the HVAC cluster focused on equipment upgrades. See images from example Basic and HVAC cluster projects in Figure 11.

Figure 11. Basic cluster (top) and HVAC cluster (bottom) example project images. Attic blown cellulose insulation (top left), attic framing air sealing (top right), gas furnace (bottom left) and split heat pump (bottom left). (*Image credit: Building America Solution Center, Image Gallery*).

Advanced HVAC: This cluster focused on the HVAC category with some Seal and Insulate expenses. The projects were generally simple (2.5-measures) and short (1-month). But the costs were significantly higher (median of $26K), almost entirely due to the cost of the HVAC measures ($23k), which were 75% heat pump installations. These represent high-cost HVAC upgrades that in all likelihood include substantial duct improvements, add-on technologies (e.g., filtration or humidity control), and other features making them much more expensive than common in-kind replacements. See images from example Advanced HVAC cluster projects in Figure 12.

Figure 12. Advanced HVAC cluster images. Heat pump outdoor unit (left), encapsulated ducts using spray foam (middle), and air-to-water heat pump with advanced filtration and outdoor air intake (right). (*Image credit: Building America Solution Center, Image Gallery*).

Large Home Geothermal: This cluster is the first cluster with greater than 50% net-energy savings and thus could be considered a "deep" energy retrofit. Compared to the three previous clusters with lower savings, Large Home Geothermal projects were much more complex (median of 9 measures) and took longer to complete (median of three months). In addition to the HVAC and Seal and Insulate categories, these projects commonly include domestic hot water (DHW) and some work in the Lighting and PV categories. These projects are characterized by being very large dwellings (4,648 ft^2), and while floor area normalized costs were moderate ($23 per ft^2), the total costs ($120K) were the highest of all the clusters. HVAC cost ($82K) was over three times that in the next highest cluster and consisted almost completely of ground source heat pump installations. See images from example Large Home Geothermal projects in Figure 13.

Figure 13. Large Home Geothermal cluster project images. Before exterior (top left), geothermal heat pump well head (top middle), drill and fill wall insulation (top right), before gas furnace HVAC (bottom left), energy recovery ventilation (bottom middle), encapsulated crawlspace bottom right). (*Image credit: Southface Institute: GoodUse Program*).

Superinsulation: This cluster represents what would typically be considered a classic "deep" energy retrofit, with aggressive envelope upgrades that make up a large fraction of the project cost. All the projects included the HVAC and Seal and Insulate categories, and many had House, Doors and Windows, DHW, and Electrical category costs. It was the second most costly cluster ($109k) and by far the most expensive normalized by floor area ($57 per ft^2). Envelope upgrades dominated the total project costs, including the Seal and Insulate category (typically $53k), Window and Door ($11k) and whole House expenses ($35k). These projects were also the most complex, having the most measures (median of 16) and longest project lengths (median of 15 months). Houses in this cluster were also significantly older (median of 40 years) than the other clusters. The high cost of this type of envelope-focused retrofit is why DOE is targeting envelope upgrades with the Advanced Buildings Consortium collaborative[11]. See images from example Superinsulation cluster projects in Figure 14.

Figure 14. Superinsulation cluster project images. Before (left), during (bottom) and after (right) exterior wall insulation upgrade. (*Image credit: Jon Harrod of Snug Planet*).

Electrification with PV: This cluster had median net-site energy savings of 72%, the highest energy savings of all the clusters. PV systems were installed in 100% of projects in this cluster, and the electrical energy production directly offset energy consumption. In addition to PV, these projects focused on the HVAC category (almost all heat pumps) and Seal and Insulate. More than half of projects upgraded to heat pump water heaters. Although it was the second most complex (median 10 measures) and second longest (median 4 months), its total cost was half that of the two other complex clusters which had lower savings. See images from example Electrification with PV cluster projects in Figure 15.

[11] https://www.energy.gov/eere/buildings/abc-collaborative

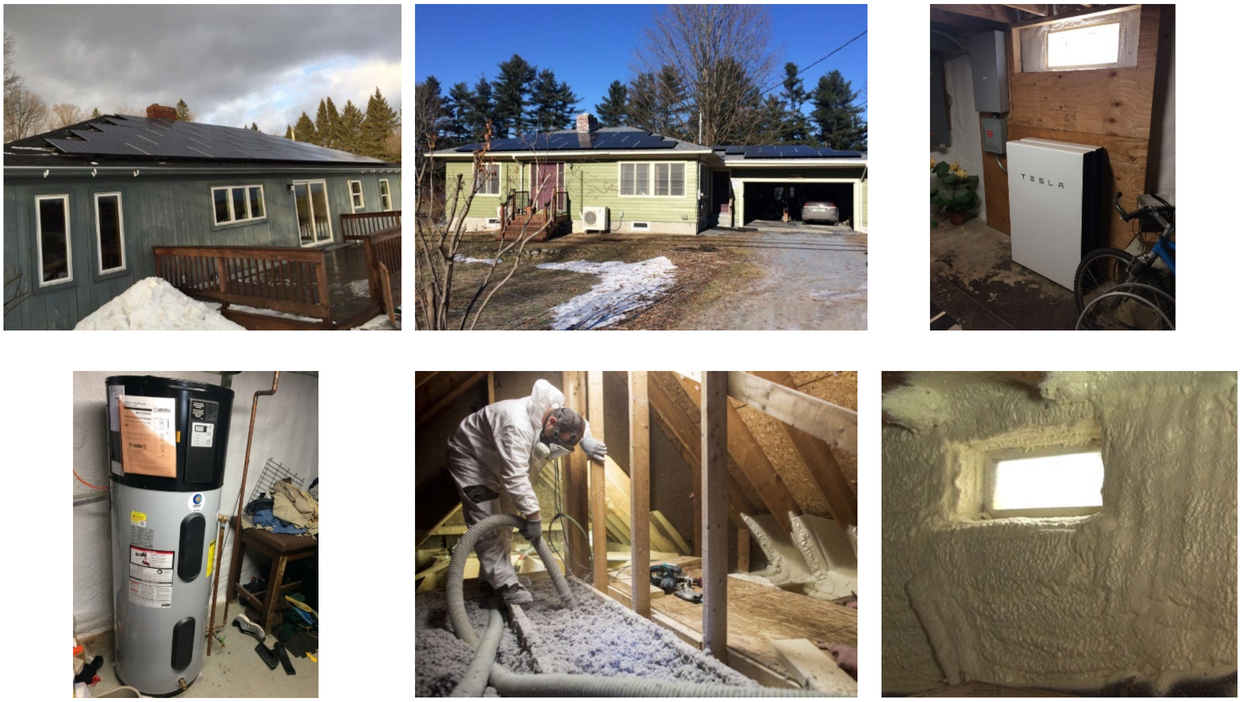


Figure 15. Electrification with PV cluster project images. Post-retrofit exterior images including solar PV (top left and middle), Tesla battery pack (top right), heat pump water heater (bottom left), cellulose attic insulation (bottom middle) and closed cell spray foam basement wall insulation (bottom right). (*Image credit: Zero Energy Now (ZEN) Program, VT*).

Table 6. Median cluster project characteristics.

Cluster	Number of Projects	Number of Measures	Vintage	Floor Area (ft^2)	Project Length (months)	Total Cost ($)	Total Cost ($/$ft^2$)
Basic	671	2	1975	1,700	1	$3,849	$2
HVAC	857	3	1977	1,713	1	$10,105	$6
Advanced HVAC	136	2.5	1971	2,426	1	$26,228	$11
Large Home Geothermal	14	9	1982	4,648	3	$120,802	$23
Superinsulation	15	16	1941	1,670	15	$109,059	$57
Electrification with PV	43	10	1953	1,987	4	$54,098	$28

Table 7. Median category cost for clusters with recorded costs in the measure category. Cells with more than 20% of projects recording a cost are bold text, and these cells are shaded if the median costs were >$5,000.

Cluster	PV	HVAC	House	Appliance	Doors and Windows	Lighting	DHW	Electrical	Seal and Insulate
Basic	$10,442	**$3,076**	$1,378	$1,019	$2,473	$129	$2,037	$2,869	**$2,965**
HVAC	$15,226	**$8,312**	$3,632	$1,601	$4,454	$166	$2,038	$476	**$1,601**
Advanced HVAC	$19,089	**$22,681**	$1,685	$1,682	$4,184	$502	$2,700	$212	**$6,657**
Large Home Geothermal	**$36,341**	**$82,283**	---	---	$67,584	**$46,255**	**$4,486**	$6,067	**$9,000**
Superinsulation	$29,262	**$13,722**	**$34,581**	$1,125	**$11,189**	$1,052	**$3,538**	**$643**	**$53,421**
Electrification with PV	**$29,443**	**$12,314**	$1,900	$1,832	$5,347	$2,864	**$2,503**	$170	**$11,193**

Table 8. Fraction of cluster projects with each measure. Cells with more than 20% of projects recording a cost are bold text and shaded.

Cluster	PV	HVAC	House	Appliance	Doors and Windows	Lighting	DHW	Electrical	Seal and Insulate
Basic	0%	**45%**	6%	2%	5%	9%	11%	0%	**76%**
HVAC	1%	**100%**	5%	5%	5%	19%	11%	1%	**47%**
Advanced HVAC	1%	**100%**	6%	1%	4%	4%	17%	4%	**35%**
Large Home Geothermal	**21%**	**100%**	0%	0%	14%	**29%**	**64%**	14%	**64%**
Superinsulation	7%	**100%**	**47%**	7%	**40%**	7%	**40%**	**33%**	**100%**
Electrification with PV	**100%**	**98%**	2%	5%	9%	7%	**53%**	2%	**91%**

Table 9 shows the energy metrics calculated for each cluster. Energy metrics include percent savings, along with floor area normalized net-site, energy cost and carbon emissions savings. Financial metrics include:

1. Net-monthly ownership costs (Monthly loan cost – monthly energy cost savings), 30-year, 3%.
2. Levelized cost of saved energy (LCOE) with a 15-year measure life and discount rate of 3%.
3. Simple payback

Median pre- and post-retrofit net-site energy use are shown in Figure 16 (see Figure 17 and Figure 18 for energy costs and carbon emissions). The distributions of project cost, percent savings and simple payback are shown in Figure 19.

Only two clusters had median CO_2 reductions greater than 50%: The Superinsulation and the Electrification with PV clusters. The high-cost cluster represents a traditional deep retrofit (i.e., strongly focused on super-insulating and sealing the existing envelope, upgrading windows, etc.). Typical envelope insulation and sealing costs in this cluster were roughly $60,000, with total project costs exceeding $100,000. The emerging trend—Electrification with PV—is a combination of solar PV, comprehensive weatherization work, and electrification of end-uses with heat pump technologies. Envelope costs are still substantial ($12,000), but investment largely shifts to installing PV, whose price has dropped by more than half over the past decade, making it much more attractive as an alternative to load reduction measures. This emerging approach is half the cost per square foot ($28 vs $57 per ft^2), the net-site savings are slightly greater (72 vs 64%) and the carbon emission reductions are substantially higher (68 vs 51%). Note that the low end of this cost range corresponds very well with the $22 per ft^2 reported in (Less & Walker, 2014) when adjusted for inflation. As a result, the simple payback, while still high (31 years) is 75% less than for the high-cost envelope-focused cluster. Consistent with long simple payback periods, the net-monthly ownership costs of the Electrification with PV cluster remain substantial ($90 per month) when financed using 30-year financing at 3% interest. The levelized cost of saved energy in these clusters exceeds utility rates in most of the country ($0.18 per kWh). On top of this, the disruption to the occupants (as assessed by project duration) is also much less with the Electrification with PV cluster, with a typical project duration of 4 vs. 15 months for the Superinsulation cluster. The other two medium cost clusters (HVAC and Advanced HVAC) have lower overall net-site energy (33 and 40%) and carbon savings (31 and 25%), but both serve as viable templates for upgrade projects that could be considered “deep retrofits” with the addition of solar PV.

These also have much more attractive financial metrics, with lower net-monthly costs, particularly for the HVAC cluster.

Table 9. Median cluster annual energy metrics.

Cluster	Net-Site Energy Savings (%)	CO_2 Savings (%)	Net-Site Energy Savings (kWh/ft²)	Energy Cost Savings ($/ft²)	CO_2e Savings (lbs. CO_2e/ft²)	Levelized Cost of Saved Net-Site Energy ($/kWh) 15-year 3% discount	Net-Monthly Cashflow ($) 30-year, 3% interest	Simple Payback (years)
Basic	20%	19%	2.3	$0.15	1.1	$0.077	-$5	15
HVAC	33%	31%	4.2	$0.38	2.4	$0.118	-$6	16
Advanced HVAC	40%	25%	6.8	$0.14	2.1	$0.155	$86	60
Large Home Geothermal	56%	39%	9.0	$0.25	3.1	$0.238	$270	82
Superinsulation	64%	51%	14.0	$0.61	5.8	$0.385	$355	120
Electrification with PV	72%	68%	14.5	$0.89	5.0	$0.178	$90	31

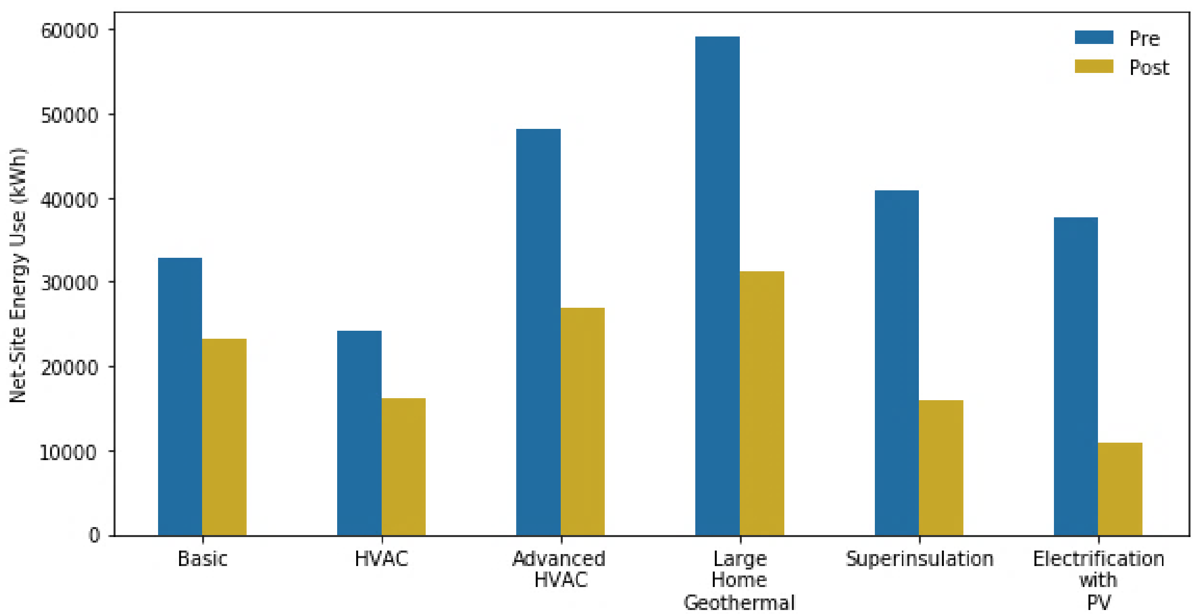


Figure 16. Comparison of Pre- and Post-retrofit total net-site energy use by cluster.

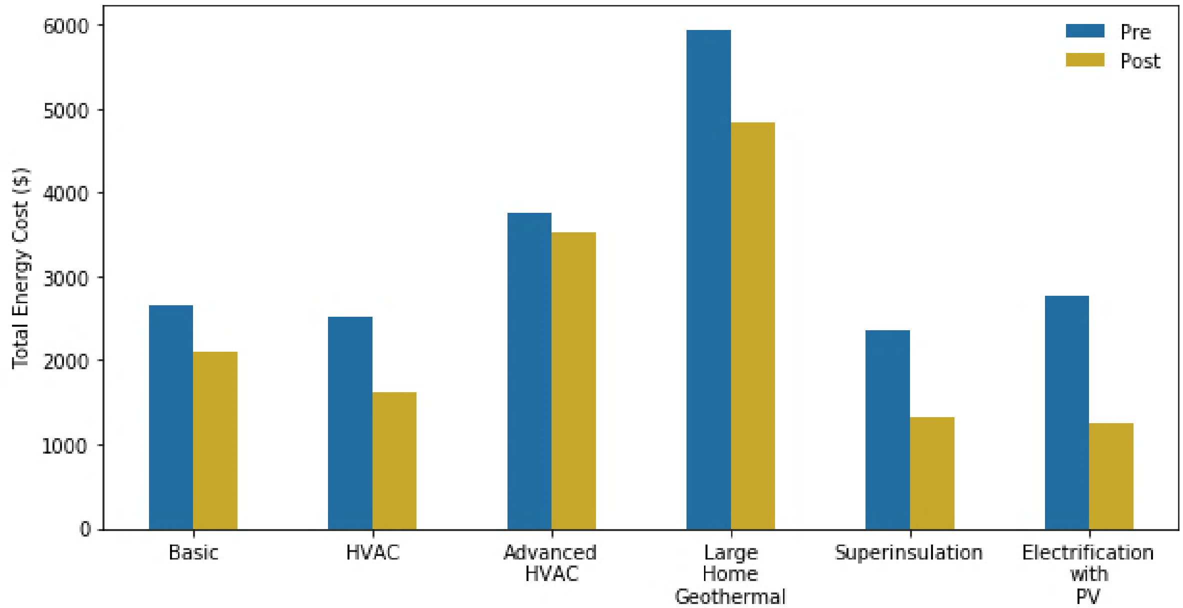


Figure 17. Comparison of Pre- and Post-Retrofit total energy cost by cluster.

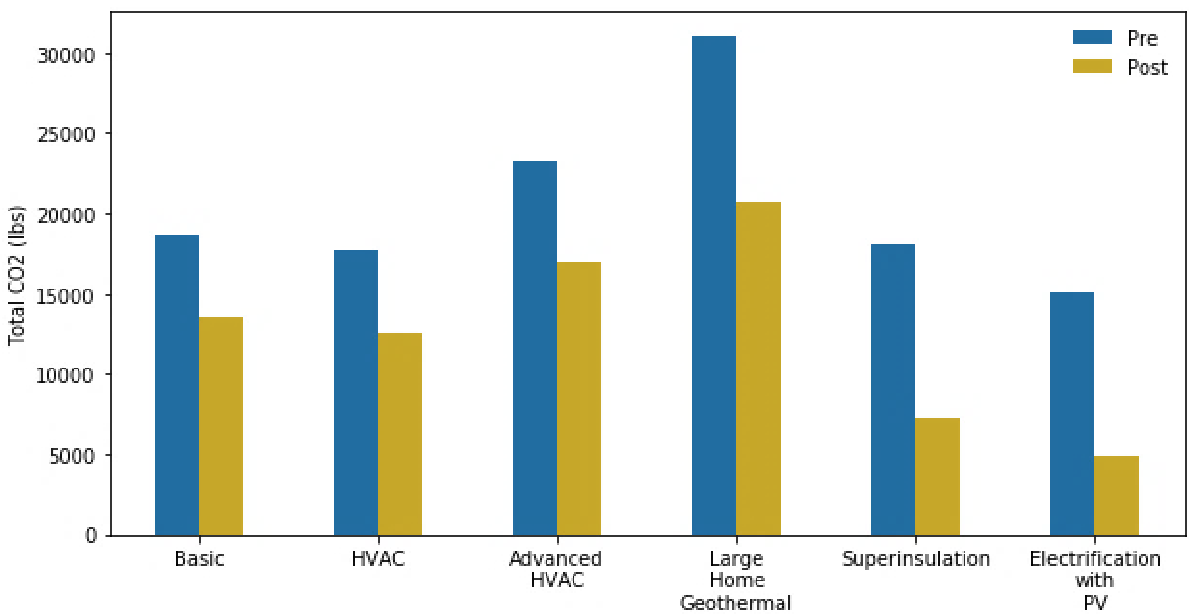


Figure 18. Comparison of Pre- and Post-Retrofit total CO_2 emissions use by cluster.

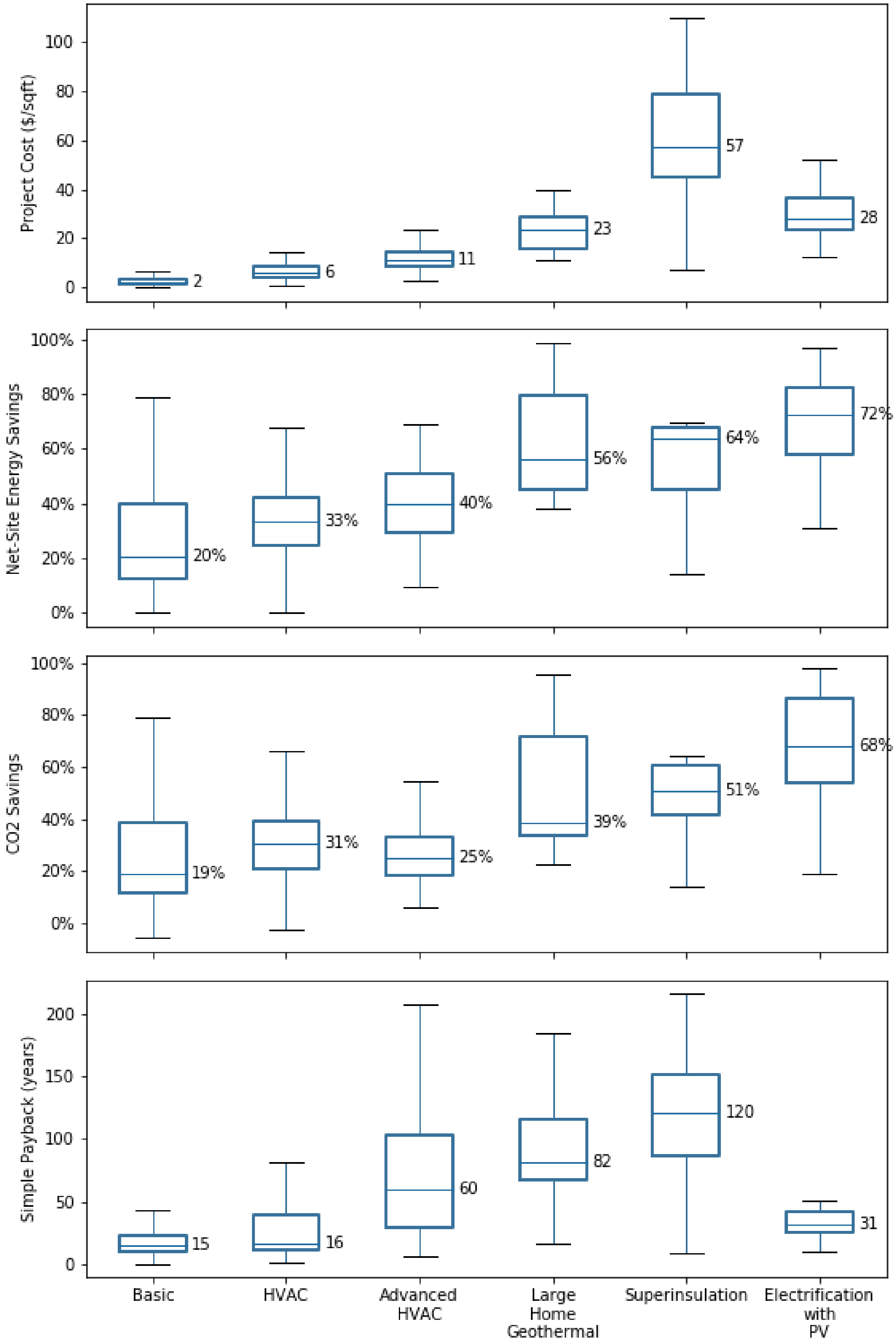


Figure 19. Distribution of four cluster metrics. The median values are shown in green, the blue box represents the interquartile range, and the black whiskers are the 5th and 95th percentiles.

4.1 Cluster Cost Stacks

To inform research aimed at reducing retrofit costs that are currently expensive, the upgrade projects were divided based on the cluster analysis described above, and a cost stack was developed for each project. The typical distributions of project expenditures were applied to the median cluster costs in order to produce these summaries. The cluster cost stacks organized by Section are shown in Figure 20. The same cost stacks are shown in Figure 21 with reduced cost categories—envelope, equipment and PV. These clusters are also shown with business gross margins/soft costs in Figure 24. Note: as in the previous section, the clusters are organized on the x-axis according to their percent carbon savings from low to high.

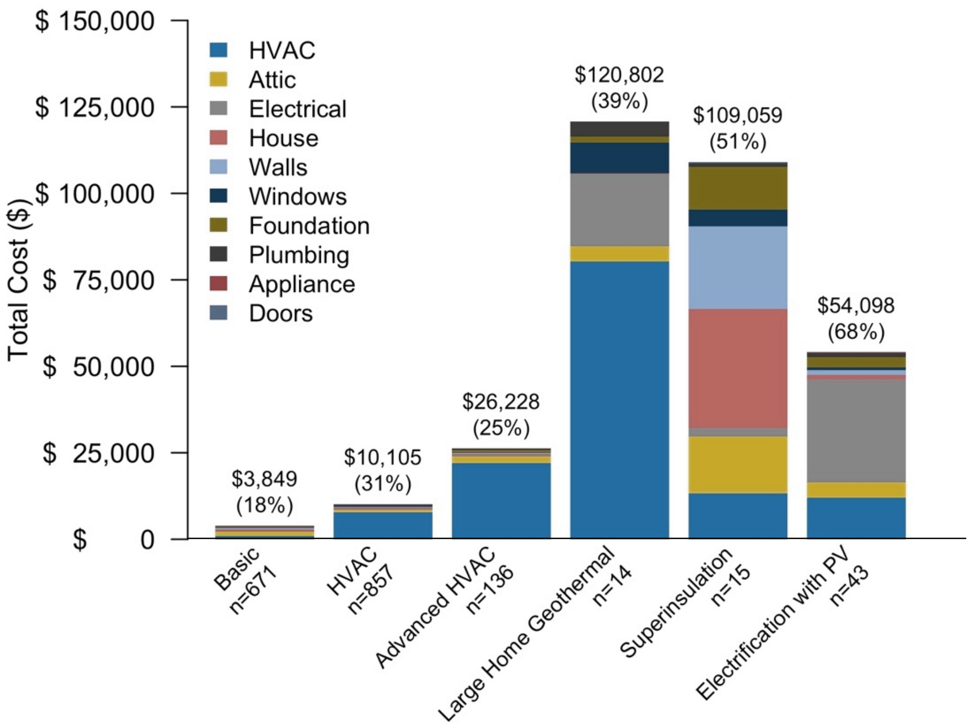


Figure 20. Cluster cost stacks by Section category. Median values of total gross project cost and percent carbon reductions.

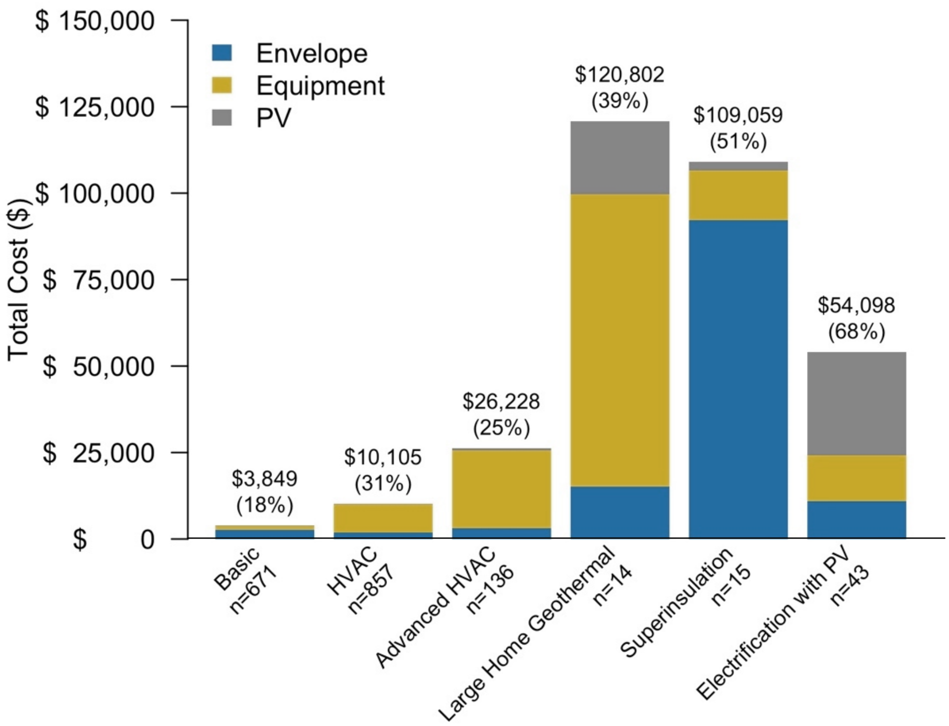


Figure 21. Cluster cost stacks with reduced cost categories (envelope, equipment and PV). Median values of total gross project cost and percent carbon reductions.

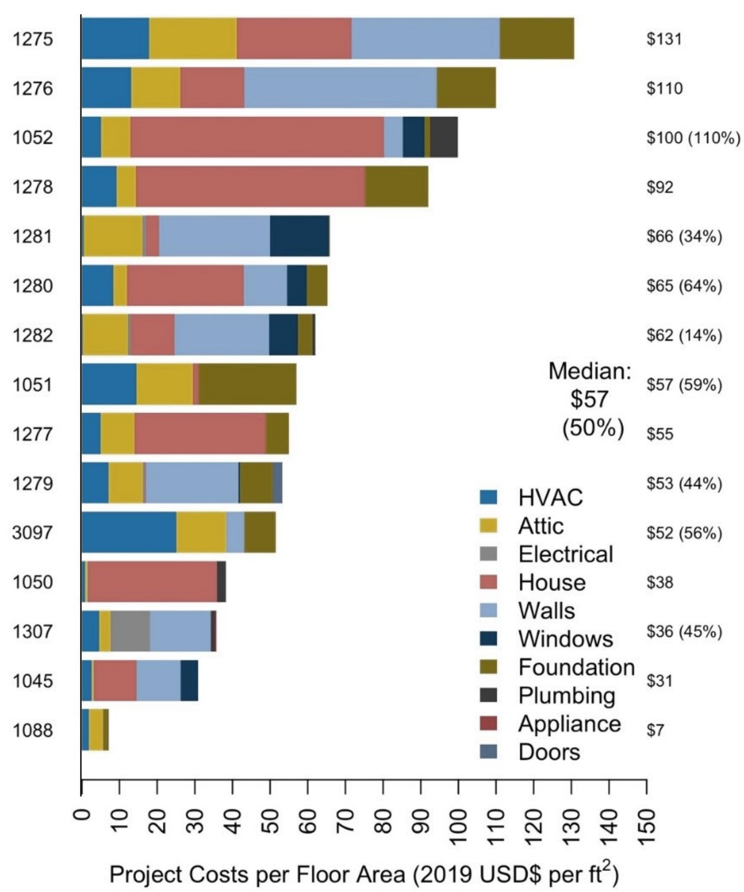


Figure 22. Superinsulation projects ordered by costs per ft². Carbon reductions shown in parentheses.

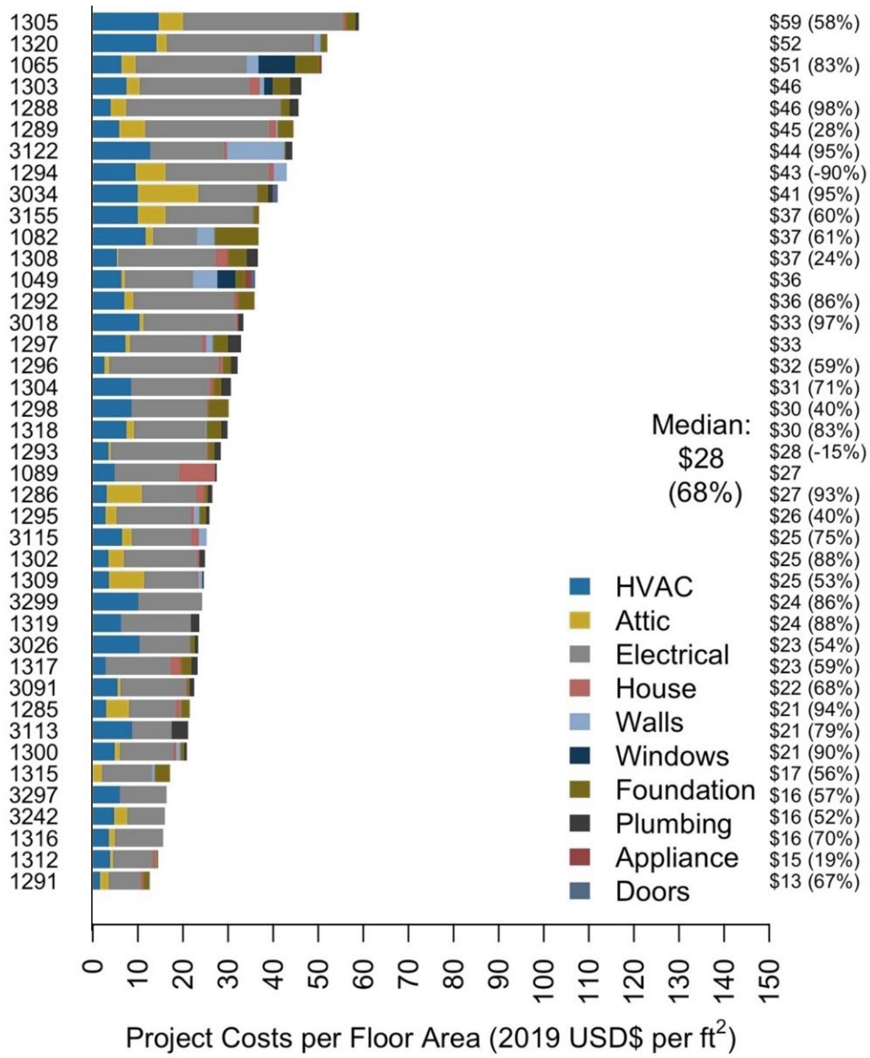


Figure 23. Electrification with PV projects ordered by costs per ft^2. Carbon reductions shown in parentheses.

APPENDIX D – Cluster Cost Stacks summarizes all the individual project cost stacks in each cluster showing net-site energy and carbon savings on a total project and per square foot basis. Here, we will focus on the two clusters that typically delivered greater than 50% energy and carbon reductions: Superinsulation and the Electrification with PV.

All projects in the Superinsulation cluster are shown in Figure 22, including upgrade costs per ft^2 of conditioned floor area and percent carbon reductions. The median project cost $57/ft^2 and reduced carbon emissions by 50%, with a corresponding net-site energy savings of 64%. The high costs of these projects are predominantly the insulation efforts in walls, foundations and attics, with some contribution of HVAC and window upgrades. In several cases, all the insulation and envelope upgrades are categorized under the House section (red bars), because no cost resolution was available at the Section level. Only one project in this cluster (1307) included PV upgrades (grey "Electrical" bar). Note, some projects did not report sufficient energy data to calculate percent carbon savings.

The Electrification with PV cluster is shown in Figure 23 with much lower median project costs of $27/ft^2 and greater typical reductions in carbon emissions of 68%. Corresponding net-site energy savings were 72%. The x-axis is scaled identically for these two figures in order to illustrate the substantially lower costs in this second cluster. In fact, only one single project in this cluster (1305) exceeded the median cost of the Superinsulation cluster. This is a much more cost-effective way to reach significant carbon and energy reductions than the envelope focused retrofits. The costs here are driven by electrical upgrades (namely PV, grey “Electrical” bars) and heat pumps for heating/cooling (blue bars). Heat pump water heater upgrades were common in this cluster (dark grey bars), but the costs were much lower. Homes in this cluster often had basic (though comprehensive) weatherization levels of attic and wall insulation and air sealing upgrades. Notably, some include large envelope costs in the attic (3034, 1286 and 1309) and walls (3122). Two projects included window upgrades (1049 and 1065).

Why are the project costs and performance so different between these two clusters?

First, envelope-focused upgrades are very complicated and expensive, particularly when they are expanded beyond typical practice in weatherization and home performance (e.g., exterior insulation or super airtightness). These efforts require unfamiliar materials, attachments, engineering design, etc. Today there is no contractor base in the US prepared to consistently deliver this work within time and budget constraints. In addition to these very high measure costs, the marginal energy cost savings attributable to these envelope investments are often modest. There are energy performance benefits to additional insulation and to the avoidance of thermal bridging, but the basic physics of heat transfer stipulate reduced energy cost savings for each incremental unit of R-value. That said, there may be substantial non-energy benefits for these efforts, including moisture performance, durability and resilience benefits. But these cannot simply be justified based on energy or carbon savings. Envelope upgrades also tend to have longer measure lives (50+ years) compared with equipment upgrades (<20 years), so an alternative economic analysis might provide some additional support to these project types over the long-term.

Second, projects in the Electrification with PV cluster focused on electrification as a core upgrade strategy. These projects tended to be located in states that have low carbon intensity of grid electricity (see APPENDIX B – Energy Unit **Conversion** for more details), and where pre-upgrade energy use and energy cost were both high. There was lots of opportunity for savings, and the fuel switching dramatically boosted carbon reductions in this cluster (68 vs. 50%). We would expect similar projects to have lower carbon savings in states with higher carbon intensity in their electricity.

Finally, the Electrification with PV cluster almost universally included installation of solar PV, which has become a lower cost and reliable means of reducing site energy, energy cost and carbon emissions in homes. Unlike with insulation, there are no diminishing returns as solar PV wattage is increased, in fact, the per unit costs go down with larger system sizes. In addition, solar PV panels have long life spans (>25 years), though inverter and associated equipment require more frequent upgrading. The impact of solar PV on household energy use is also more predictable and is less dependent on pre-retrofit conditions, occupant activities or quality installation (assuming low levels of shading and good orientation). Combined with the other two reasons discussed above, these features led to half the cost per ft^2 and substantially better carbon performance. Notably, the attractiveness of PV in energy upgrade projects is limited by regulations around net-metering, which can substantially impact household economics. Also, as PV production increases on the grid, on-site energy storage or demand shifting may be required in order to avoid detrimental grid effects, including the shedding of unused renewable electricity. These dynamics can shift the cost and benefits of solar PV in home upgrades.

Finally, (Less et al., 2021) have reported that gross margins (i.e., business expenses, soft costs, etc.) comprise on average 47% of energy upgrade project costs (see Section 12.3). This suggests that 47% of the envelope, equipment and PV cost segments should be shifted to gross business margins. An example of this sort of cost breakdown is shown in Figure 24. Under this scenario with substantial gross margins, the actual materials, labor and equipment costs for the upgrade measures are roughly one-half of the total expenditures.

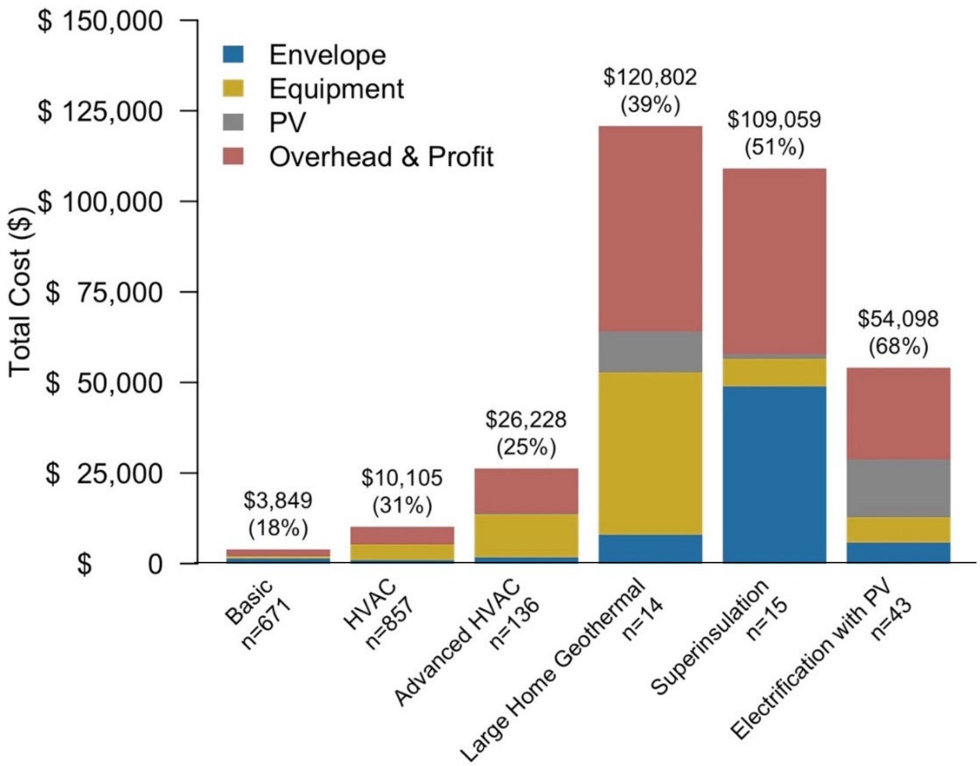


Figure 24. Cluster cost stacks with gross margins (47%) and reduced cost categories (envelope, equipment and PV). Median values of total gross project cost and percent carbon reductions.

4.2 Cluster Cost-Effectiveness and Required Cost Compression

In this section, we describe the amounts of cost compression that are required to make each cluster of projects cost-effective/cost-neutral. We define "cost-effectiveness" in this research as a comparison between a project's actual costs and the present value of the project's reported energy cost savings. We frame the energy cost savings of each project as a loan payment capable of supporting some total loan principal amount (i.e., the supported project cost). The total loan principal supported by a given amount of energy cost savings varies according to the loan terms (i.e., loan repayment period and interest rate), with higher principal amounts with longer repayment periods and lower interest rates. When a project's actual cost is higher than the supported loan principal, then the monthly cost of the loan exceeds the monthly energy savings, and home monthly ownership costs increase. When a project's actual cost is less than or equal to the supported loan principal, then the homeowner experiences net-savings, with reduced monthly ownership costs. To be considered "cost-effective", our assessment assumes monthly cashflow should be neutral or reduced post-retrofit (i.e., ownership costs are the same or reduced). Any project whose actual cost is greater than its supported loan principal needs its costs to be reduced (or compressed) in order to be cost-effective/cost-neutral.

For each project in the database, we derived the present value of energy savings and compared this with the actual project costs. From this, we derived the required cost compression and supported cost values for each project (see Methods Section 2). Here, we analyze the results according to the project clusters described in Section 4.

The median supported project cost (blue) and required cost compression (yellow) are shown for each project cluster in Figure 25, assuming a 30-year loan with 3% interest rate. Based on these assumptions, the first two clusters are already cost-effective, because the actual projects cost less than the loans that could be supported by the energy cost savings. For these projects, we expect the net-monthly cashflow to be positive (i.e., the savings are greater than loan costs). The remaining clusters, including all clusters with >50% average savings, require substantial cost compression in order to be cost-effective/cost-neutral. The required compression ranges anywhere from $20k to $91k in cost reductions. The Electrification with PV cluster is nearest to being supported by the energy cost savings, with a required 37% percent reduction in project cost ($20k). Upgrade projects achieving the level of cost savings reported for the Electrification with PV projects could cost-effectively support a project costing roughly $34k. In contrast, projects with energy cost savings equivalent to the Superinsulation projects must not exceed total costs of $18k to be cost-effective.

As noted above, loan costs are not included in these plots, but if they were, the loan costs could simply be added to the Required Cost Compression values. For example, the Electrification with PV projects would have loan costs of $28,011 over a 30-year loan at 3% interest, which would increase the Required Cost Compression from $19,867 to $47,878, with the supportable project cost ($34,232) representing only 42% of total costs ($82,109).

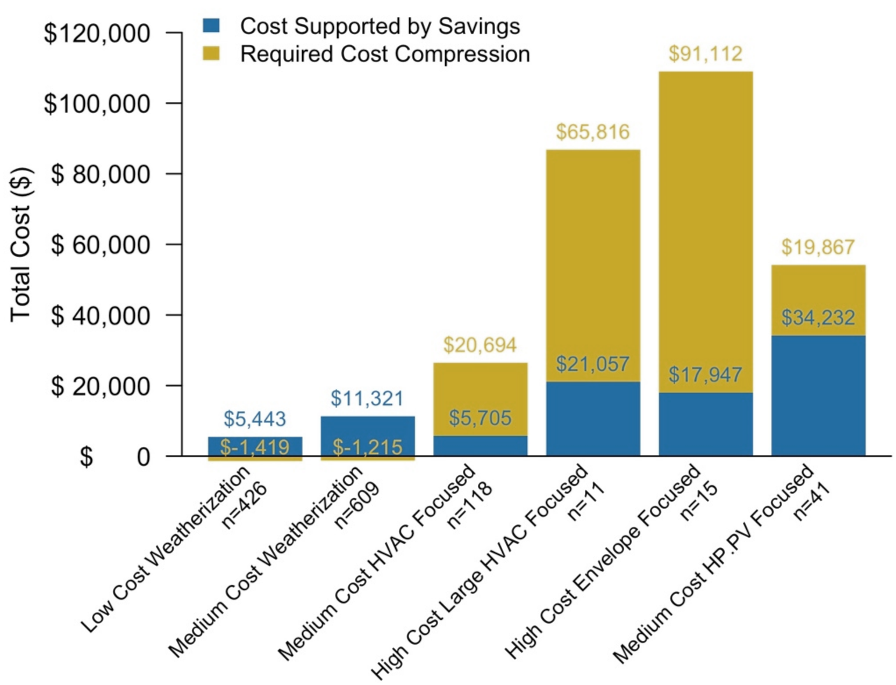


Figure 25. Required cost compression for each project cluster. 30-year, 3%.

The most direct way to compress costs for homeowners is to provide rebates and incentives. To illustrate the potential impact of a 25% incentive for home energy upgrade projects, we show these same clusters with a 25% rebate in Figure 26 (grey bars show the 25% rebate). These rebates are most impactful in the more expensive project clusters, and we observe that the electrification cluster has only $6,342 (12%) of remaining cost compression required after such a rebate. Even after rebates, the other two clusters with >50% savings (Large Home Geothermal and Superinsulation) still require massive cost compression amounting to $44k to $64k per project.

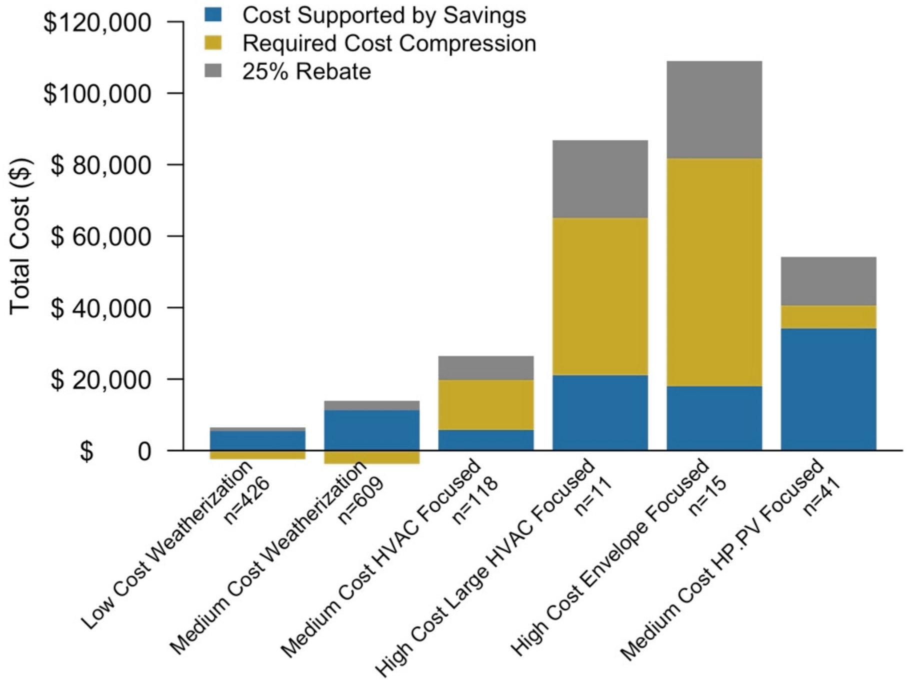


Figure 26. Required cost compression for each project cluster with a 25% rebate assumption. 30-year, 3%.

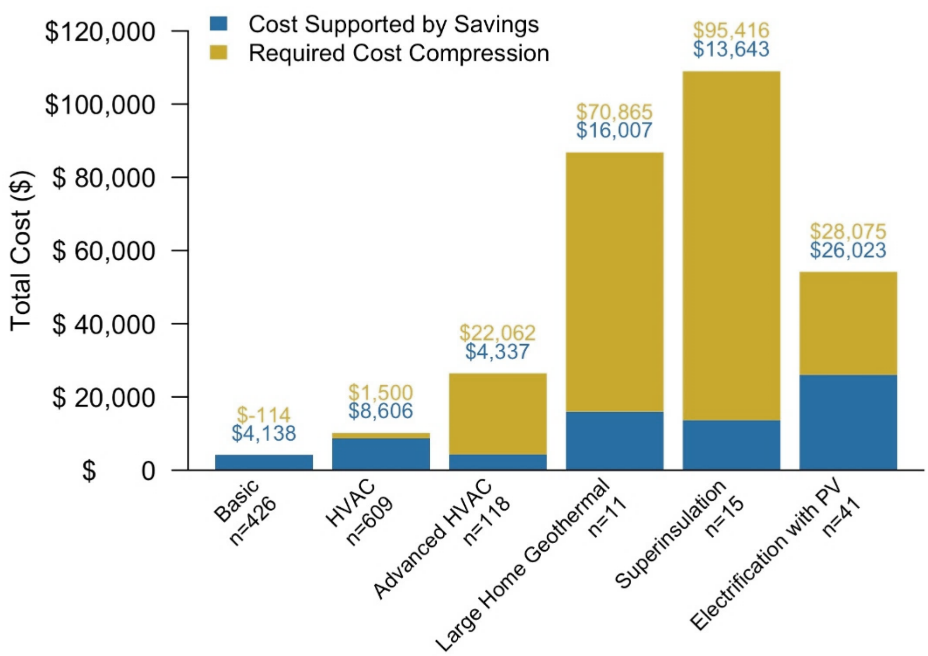


Figure 27. Required cost compression for each project cluster. 20-year 8%.

Using different assumptions for this analysis leads to very different results. For example, the same analysis using a 20-year term with 8% interest is shown in Figure 27. Based on these terms, none of the clusters are currently cost-effective. The Electrification with PV cluster, which in the previous analysis was closest to being cost-effective, now requires $34k (64%) of cost compression. Rebates are still very helpful, but the challenge of reducing upgrade project costs by 64% remains very high. To be cost-effective, such Electrification with PV projects should not exceed roughly $20k in project cost.

4.3 Compressed Cluster Cost Stacks

Finally, we can combine this cost compression analysis with the cluster cost stacks described in Section 4.1, in order to characterize a compressed cost stack that would be cost-effective under current project costs and utility prices. We show the compressed cost stacks for each cluster using the 30-year, 3% assumptions in Figure 28. These examples compressed cost stacks represent a proportional reduction across all cost categories. Actual cost compression may focus on certain elements of a project more than others. For example, the majority of cost reduction could come from lower PV costs, leaving equipment and envelope costs unchanged. Note that the results here are sensitive to loan term and interest rate and these results should only be used as general guidance.

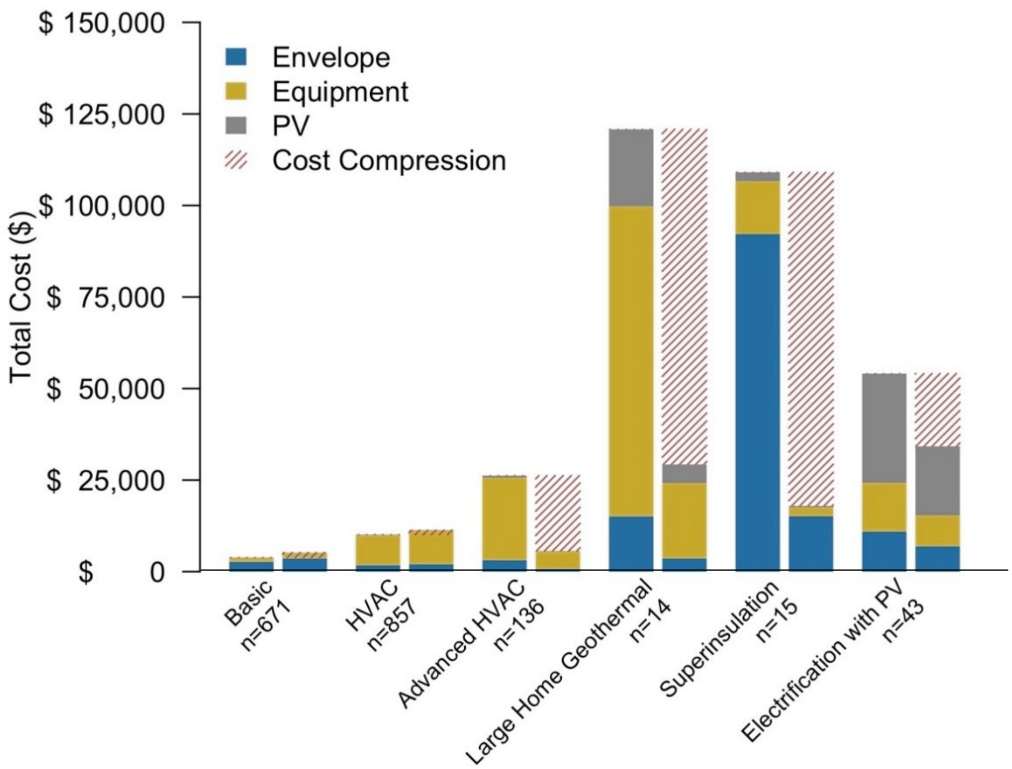


Figure 28. Current and compressed cluster cost stacks. 30-year, 3%.

Greater detail is shown for the Electrification with PV cluster in Figure 29 assuming 30-year, 3% terms (see Figure 30 for all financing terms). Again, these reductions are proportional across all cost categories. Given these assumptions, envelope upgrade costs need to be reduced from roughly $11k to $7k, equipment costs from $13k to $8k, and PV costs from $30k to $19k. Under these compressed costs, the typical project in this cluster would be cost-effective over 30-years at 3% interest. For comparison, the Superinsulation cluster is shown in Figure 31 at 30-years, 3%. These projects require massive cost compression in order to be cost-effective. For example, envelope upgrades would need to be reduced from roughly $92k to $15k.

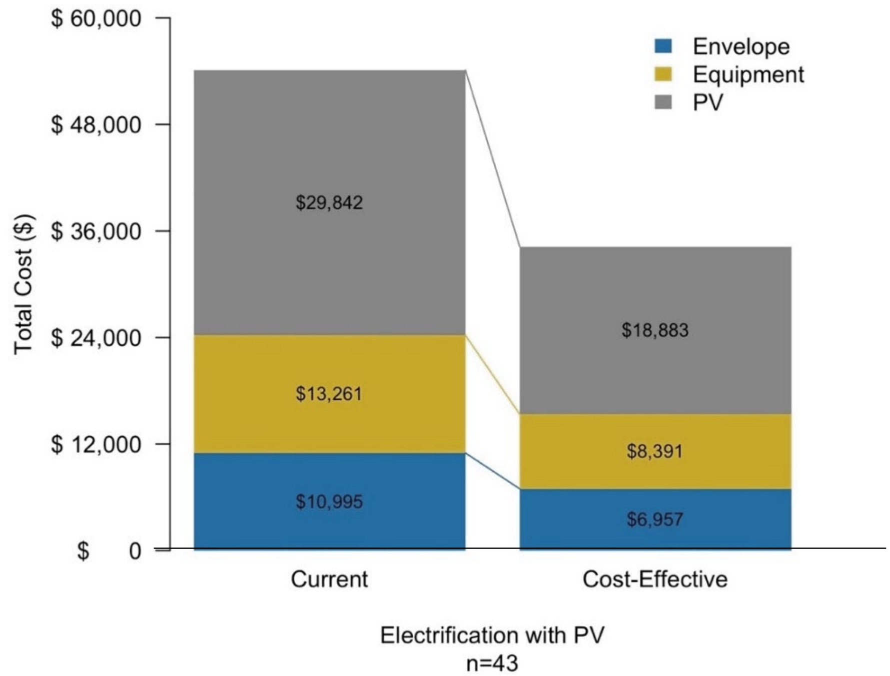


Figure 29. Electrification with PV cluster current and cost-effective cost stacks. 30-year, 3%.

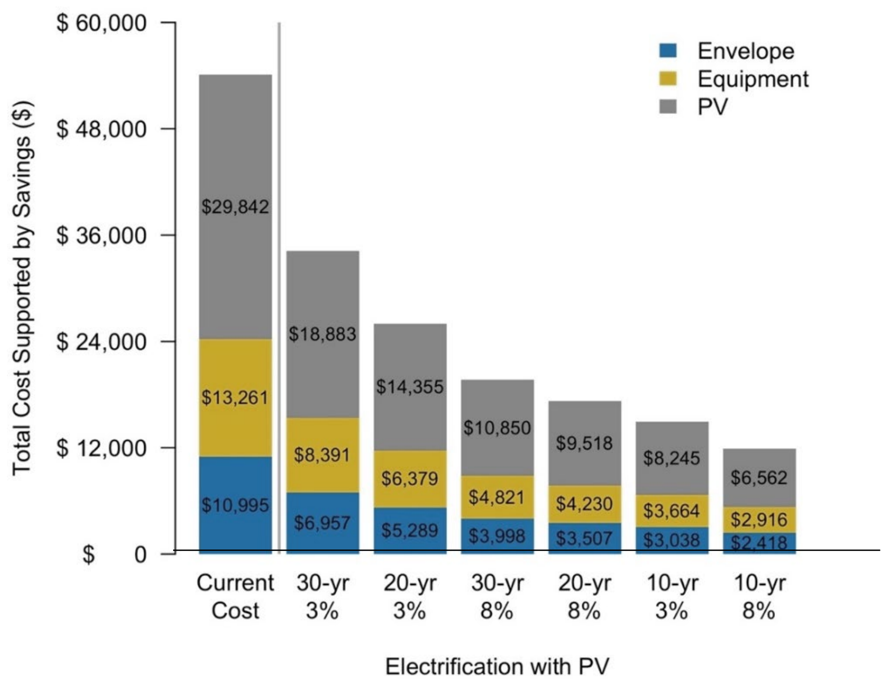


Figure 30. Compressed cost stacks for all analysis terms, Electrification with PV projects.

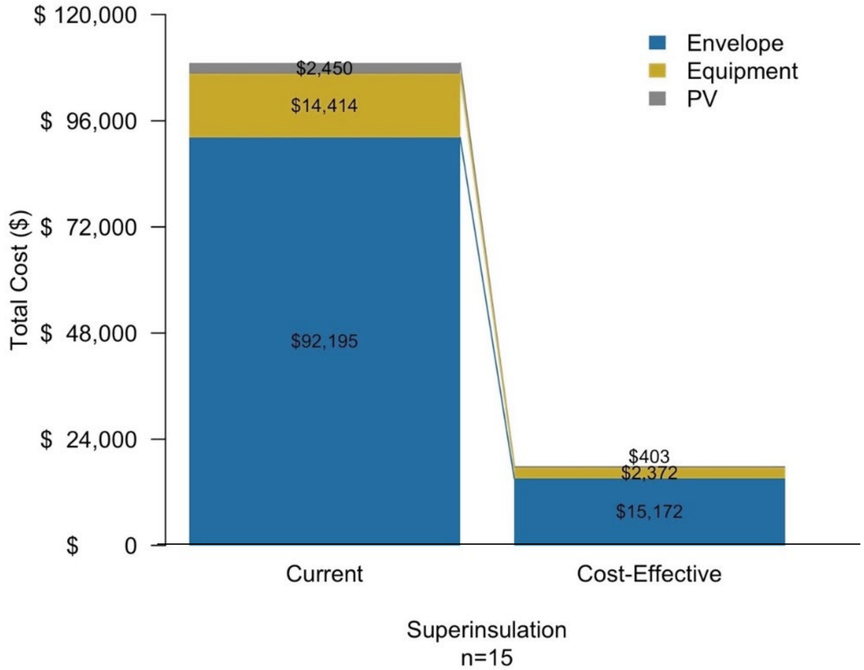


Figure 31. Superinsulation cluster current and cost-effective cost stacks. 30-year, 3%.

5. Archetypal Projects

In addition to summarizing the individual projects, we also created archetypal projects whose characteristics were determined from the database. Project costs and percent CO_2e savings were predicted using regression models for each of 48 archetype projects. The archetypes represent an example dwelling that matches the typical characteristics of homes in the DER database, including being a 1,768 ft^2, 1-story, wood framed, single-family dwelling with a basement foundation, built in 1970. A series of archetypal projects for this home were assembled from the bottom-up using combinations of measures in each of three categories:

- **Envelope**
  - None
  - Weatherization (Wx)
  - Home performance (HP)
  - Deep Energy Retrofit (DER)
- **Equipment**
  - None
  - Electrification (Elec)[12]. Includes space heating, cooling and water heating.
  - Gas (Gas). Includes only space and water heating, no cooling.
- **PV**
  - None
  - Small, 3.35 kW
  - Medium, 6.7 kW
  - Large, 10 kW

Within each category (Envelope, Equipment, PV), the sub-bullets represent different approaches within the category (e.g., "Home Performance (HP)" in "Envelope"). These categories were assigned specific sets of retrofit measures representing typical practice in retrofits. The measures are detailed for envelope measures in Table 10, for equipment (HVAC/DHW) in Table 11, and for PV in Table 12. The total costs for each category of these archetypal retrofits are shown in. All archetypal projects include the measures listed in the "None" envelope category, such as LED lighting, door weather-stripping and low-flow plumbing upgrades. The "Upgrade" columns in each table represent the information required to characterize each specific measure type in the database. For example, a heat pump is characterized by its cooling and heating efficiencies (SEER and HSPF), along with its capacity (tons). Attic floor insulation is specified by its R-value, depth and treatment area. Total costs are summed for each category in Figure 32. For example, the Home Performance Envelope upgrade measures cost a total of $12,789 ($7.23 per ft^2). The costs for each individual measure were either predicted using random forest regression models built for each individual measure, or they were predicted using the median cost recorded in the energy upgrade database. Measures using median cost are indicated by the "*" symbol in the tables below.

[12] This does not include electrification of cooking or clothes drying, nor does it explicitly include the cost of panel/service upgrades. Electrical costs embedded in the measures recorded in the database (e.g., running an electrical circuit for a heat pump installation), are implicitly included in the costs for those measures. Clothes dryer replacement median costs were $1,966, and no cooking appliance upgrade costs were recorded. RSmeans estimates for panel upgrade to 200A electrical service is $1,954 for demo and panel installation, which does not include any re-wiring of circuits in the home.

Table 10. Envelope measure specifications in archetype projects. Note: (*) indicates costs estimated using median values from the database. All other costs estimated by random forest regression models.

	Predicted Cost ($)	Upgrade
None		
Door weather stripping*	$99	---
Lighting upgrades	$387	17 units
Low flow faucet*	$19	1 unit
TOTAL	**$505**	**$0.29 per ft²**
Weatherization (Wx)		
Attic floor insulation, R60	$4,402	R-60
Door weather stripping*	$99	---
Lighting upgrades	$387	17 units
Seal envelope, typical*	$831	ACH_{50} 13 pre, 8.2 post
Duct seal, typical*	$849	CFM_{25} 329 pre, 97 post
Low flow faucet*	$19	1 unit
TOTAL	**$6,587**	**$3.73 per ft²**
Home Performance (HP)		
Attic floor insulation, R60	$4,402	R-60
Door weather stripping*	$99	---
Lighting upgrades	$387	17 units
Foundation floor insulation, R25	$2,150	R-25
Seal envelope, typical*	$831	ACH_{50} 13 pre, 8.2 post
Local exhaust	$917	---
Duct seal, typical*	$849	CFM_{25} 329 pre, 97 post
Low flow faucet*	$19	1 unit
Drill and fill walls, R13	$3,135	R-13
TOTAL	**$12,789**	**$7.23 per ft²**
Deep Energy Retrofit (DER)		
Roof insulation, R35	$13,575	R-35
Door weather stripping*	$99	---
Lighting upgrades	$387	17 units
Foundation wall insulation, R18*	$6,794	R-18
Seal envelope, aggressive*	$1,246	ACH_{50} 19.1 pre, 5.9 post
New Ducts	$3,675	R-8
HRV	$1,754	---
Low flow faucet*	$19	1 unit
Drill and fill walls, R13	$3,135	R-13
Exterior wall insulation, R16*	$7,712	R-16
Gable wall insulation, R21*	$796	R-21
Window replacement	$14,746	U-value 0.32, 0.29 SHGC, 9 units
TOTAL	**$53,938**	**$30.51 per ft²**

Table 11. Equipment measure specifications in archetype projects.

	Predicted Cost ($)	Upgrade
Electrification (Elec)		
Ductless Heat Pump	$11,879	SEER 19, 11 HSPF
Heat Pump Water Heater	$2,875	Gallons 50, 3.15 EF
TOTAL	**$14,757**	**$8.35 per ft²**
Gas		
Gas Furnace	$5,066	AFUE 95, 64 kBtu/hr.
Gas Tankless Water Heater	$3,720	EF 0.87
TOTAL	**$8,786**	**$4.97 per ft²**

Table 12. PV measure specifications for archetype projects.

	Predicted Cost ($)		Upgrade
Small	$14,440	$8.17 per ft²	3.35 kW
Medium	$21,992	$12.44 per ft²	6.7 kW
Large	$24,669	$13.95 per ft²	10 kW

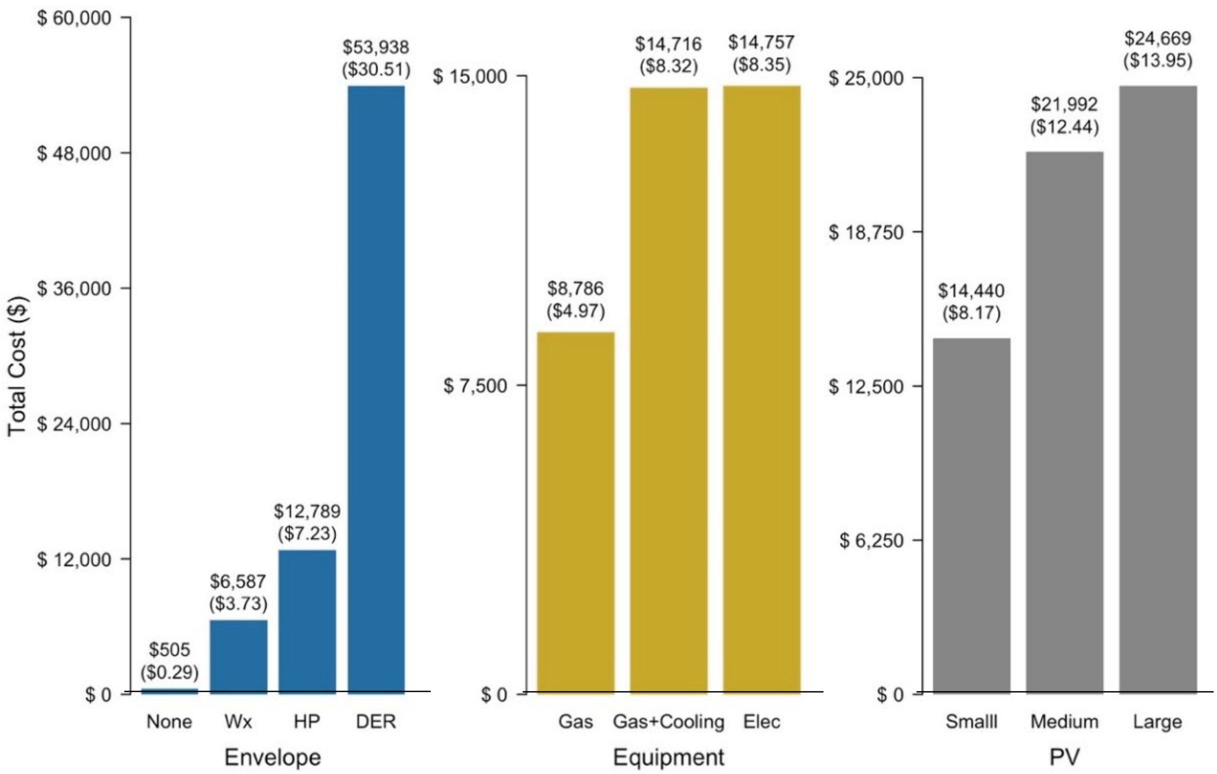


Figure 32. Archetypal project costs in each category (Envelope, Equipment and PV) for each set of archetypal retrofit measures. Costs per ft² are shown in parentheses.

The total project costs assembled from the measures listed in the tables above are plotted in Figure 33 binned into 10% segments by the percent carbon savings predicted by regression models. Smaller disaggregation below 10% is not warranted, based on the average error (RMSE) of 12% from the regression model cross-validation. The projects are sorted by total project cost within each savings 10% bin, which provides an estimate of the low and high boundaries of project costs that are expected to save certain amounts of carbon. Projects in the lowest savings bins commonly address only one cost category, or at most two cost categories (e.g., equipment and envelope but not PV, or envelope and PV but not equipment). These lower savings projects rarely include PV systems, and they never include PV and equipment upgrades.

We focus our remaining discussion on the projects with savings >50%. The subset of projects with predicted carbon reductions of 51-60% are shown in Figure 35 with a reduced number of cost categories (i.e., envelope, equipment and PV), and projects with predicted savings >60% are shown in Figure 34. All of the lowest cost projects in the 51-60% and >60% savings bins include solar PV systems, and all of the highest cost projects in each savings bin include energy retrofit envelope upgrades. In projects saving >60% carbon, the lower cost projects more commonly include electric heating and hot water (2/3 vs. 1/3 for gas).

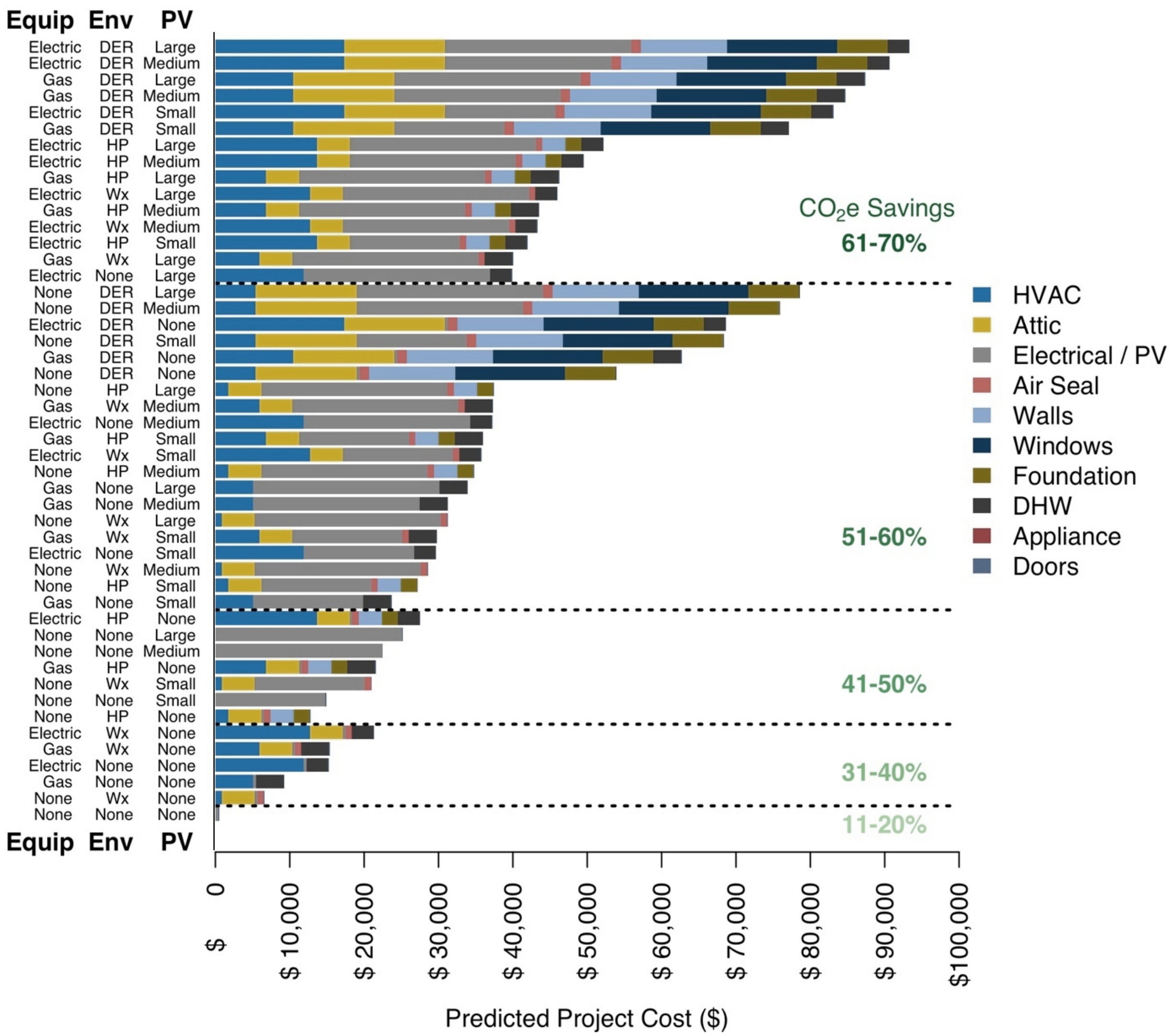


Figure 33. Archetypal upgrade projects binned by net-carbon savings.

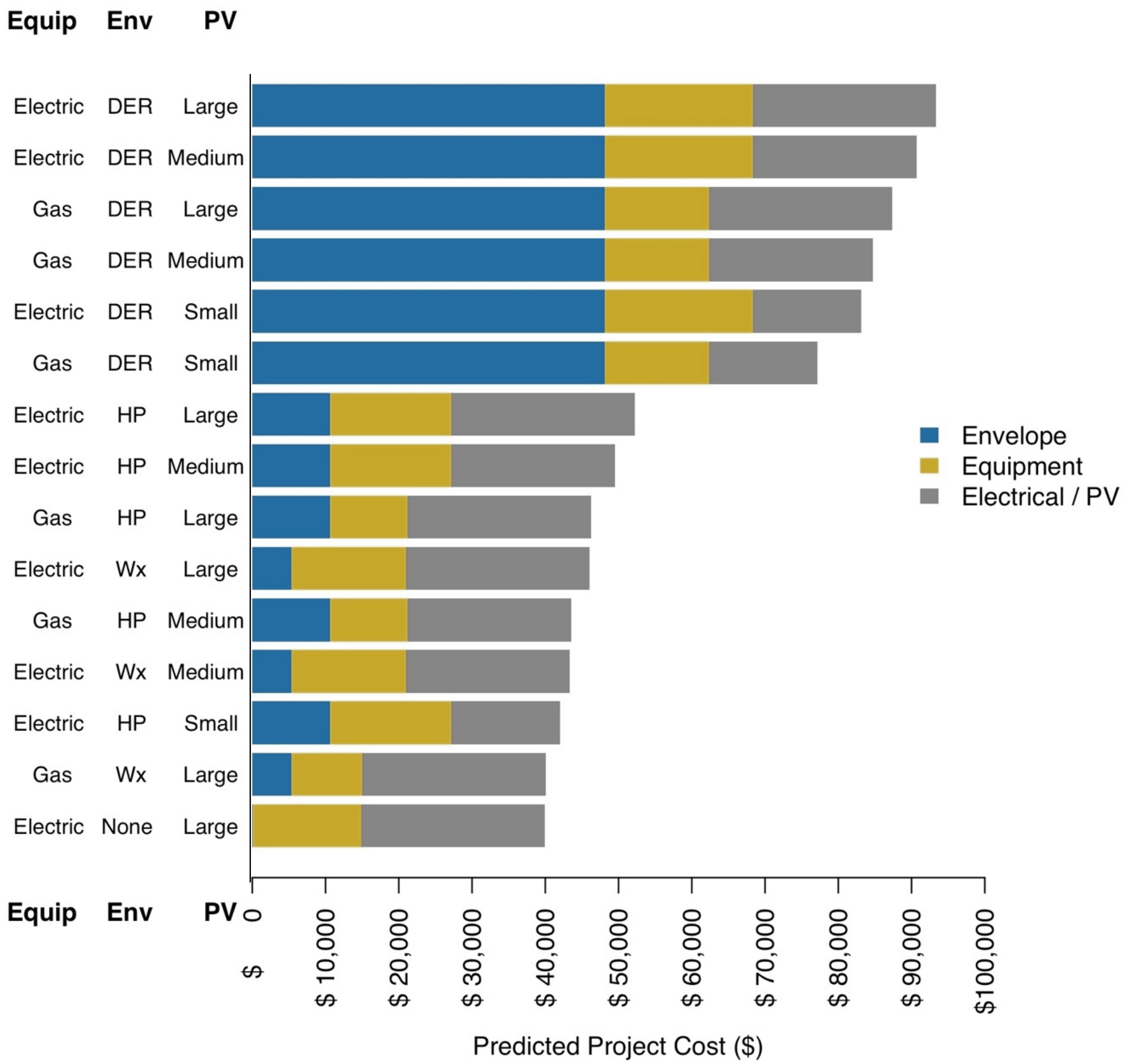


Figure 34. Archetypal upgrade projects predicted CO_2e savings >60%.

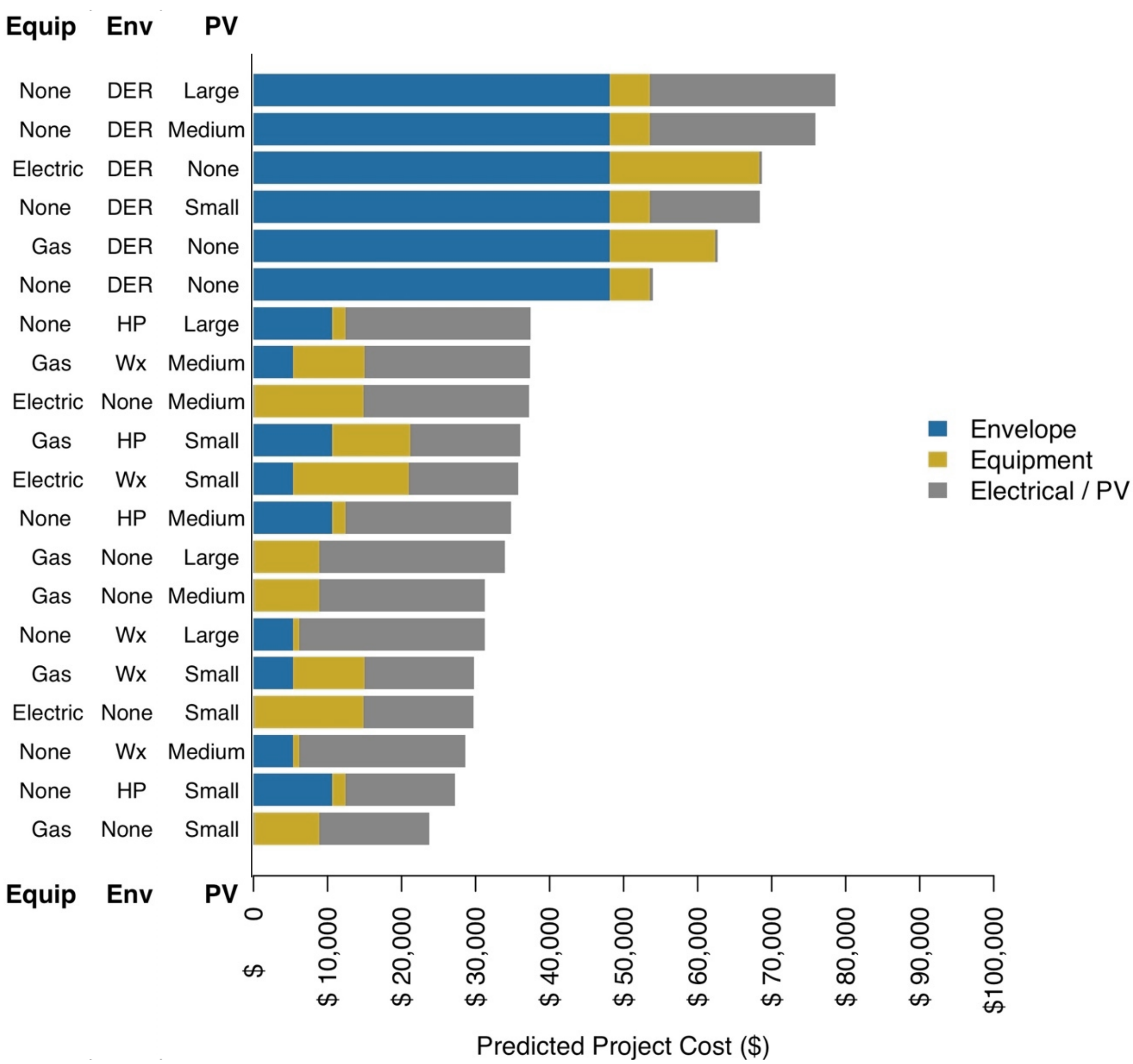


Figure 35. Archetypal upgrade projects predicted CO_2e savings 50-60%.

It is important to note that the energy savings are based on regression models and not engineering models, so this approach makes some obvious errors. For example, we know that installing a Large vs. Medium PV system will reduce net-site energy use. Any engineering analysis would show this to be the case. Yet, these projects commonly fall into the same savings bin in the plot (holding all other measures equal), which makes it look like there is no difference in performance based on the size of renewables installed. Regression-based energy predictions for each project would show marginally higher savings for the larger PV investment, but not enough to push the project into a different savings tier. This is important to keep in mind when interpreting these regression-based results—the energy outcomes are not necessarily identical, they are just indistinguishable given the accuracy of the prediction method. At the same time, the cost of the larger PV system is accurately reflected, which makes these cases look less cost-effective. Another issue with regression vs. engineering models is that there is no controlling for measure interactions. For example, the HVAC costs in each archetype are based on identical system sizes, irrespective of the level of envelope upgrades. It is possible that the “DER” and “HP” comprehensive envelope upgrades would be able to install smaller capacity equipment than the “None” and “Wx” envelope categories. For example, based on the costs reported in the database, a half ton reduction in capacity would reduce the cost by about $1,250.

In these archetypal projects, for homes currently without cooling, electrification equipment upgrades addressing space conditioning (heating and cooling) and hot water are more expensive than projects using gas equipment ($14,754 vs. $8,786). This cost difference is almost exactly the cost to separately add cooling: $5,930 (see Section 10.1.3). This implies that there is no cost premium for upgrading to electric systems – so long as we are comparing like-for-like upgrades: i.e., adding both heating and cooling to a home.

Heat pump installation was also an important variable in predicting carbon savings. Despite the higher first costs of electric vs. gas equipment (assuming no cooling is included), electrification projects were just as likely to be amongst the lowest predicted costs for a given savings tier. For example, the lowest cost project in the 61-70% tier is an electrification upgrade, combined with weatherization and a small PV system. This suggests that electrification can be achieved at comparable total project cost to gas equipment for a given savings tier, while locking in long-term carbon benefits as the grid becomes cleaner.

These archetype costs show that the cost of achieving at least a 50% energy savings is substantial – at least $25,000. The lowest cost ways to do this depend on the use of PV to offset energy use rather than substantial load reductions through envelope upgrades. To get over 60% savings requires a combination of moderate envelope improvements and replacement of HVAC and DHW together with PV, with a minimum cost of about $40,000. Bear in mind that these are archetypal costs and could be higher or lower depending on the specifics of the home being retrofitted, its location, etc., but they do give us guidance on what will be lower-cost approaches for achieving particular energy saving targets.

Of note in this analysis is that it includes only technologies and approaches that are currently happening in the upgrade market. Some emerging technologies are likely to have a big impact. For example, thermal and electric storage systems that are primarily intended to allow for time shifting of electricity use that limits the demands placed on the electric distribution grid. While this will add cost to a home upgrade, there are potentially large financial incentives due to time-of-use electric rates and/or peak demand charges. While beyond the scope of the current study, emerging technologies like this need investigation in the future.

6. Comparison with NREL Measure Cost Database

Prior to this effort to catalogue the cost of deep energy retrofits, the primary source for retrofit cost information used in home energy analysis and optimization was the NREL efficiency measure data base (NREL EMDB)[13]. The NREL EMDB is used in tools, including BEopt, Home Energy Saver, ResStock, and others. Due to its widespread use in analysis tools, we have compared a subset of the measure-level costs reported in the DER database against those included in the NREL data source (see Table 13 for a comparison of upgrade measures). The measure types are organized by the Section they address. We have focused on comparing common measures that were reported frequently in our dataset (e.g., heat pumps, air sealing), along with measures representing important elements of home energy upgrades (e.g., ventilation equipment).

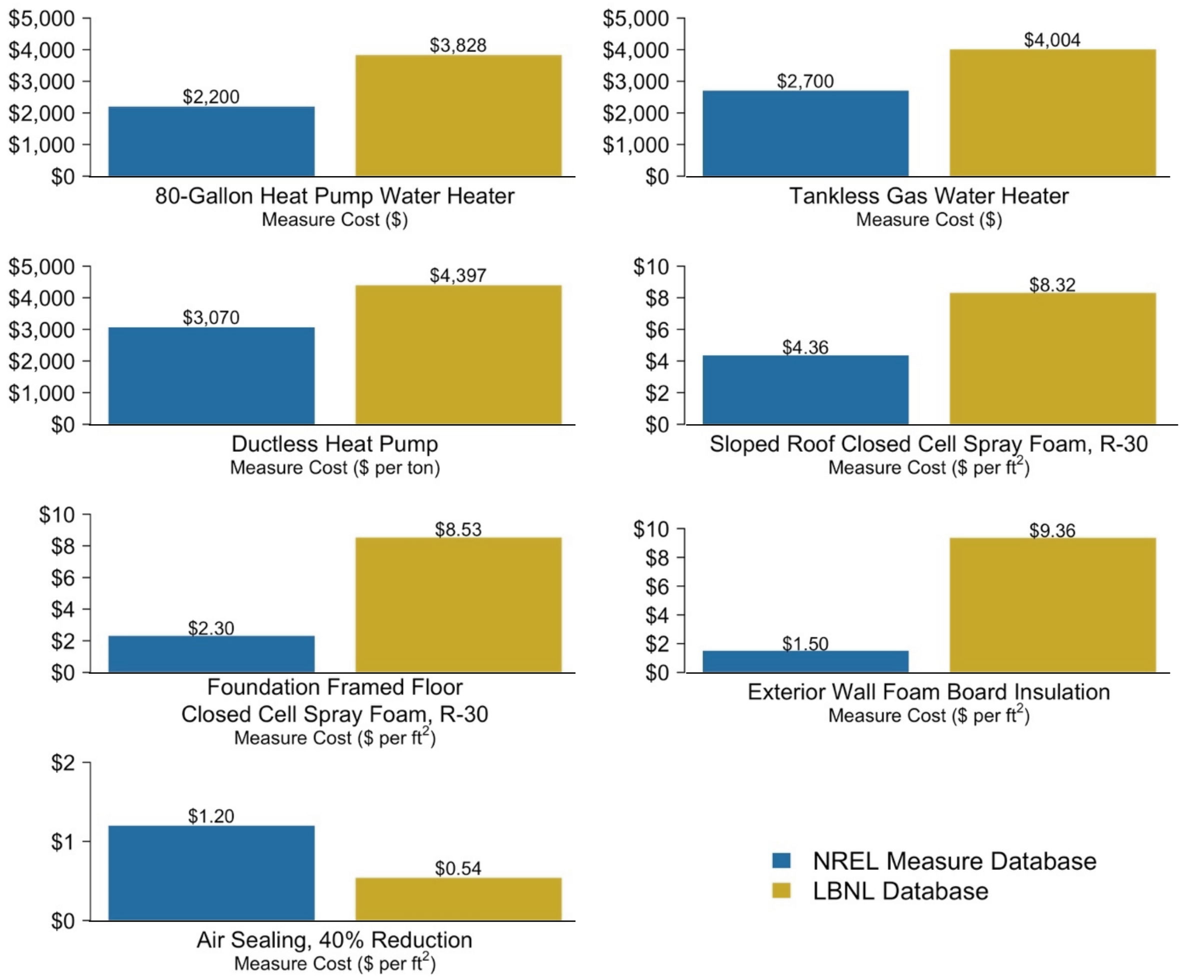


Figure 36. Comparison of typical measure costs between the LBNL and NREL efficiency measure databases.

[13] https://remdb.nrel.gov/index.php

Table 13. Comparison of measure costs between the LBNL DER database and the NREL efficiency measure database[14].

	LBNL Database	NREL EMDB
WATER HEATING		
Electric Heat Pump	• $2,242 (50-gal, EF 3.2) • $2,763 (65-gal, EF 2.33) • $3,828 (80-gal, EF 3.45)	• $2,000, range $1,400-$2,600 (50-gal, EF 2.0) • $2,200, range $1,600-$2,900 (80-gal, EF 2.35)
Tankless Natural Gas (DHW) Water Heater	• $4,004	• $2,700 (EF 96)
HVAC		
Ductless Heat Pump	• $4,397 (No evident variability by efficiency.)	• $3,070 1-ton, SEER 18, 9.6 HSPF • $3,182 1-ton, SEER 23, 10.5 HSPF
Gas Furnace	• $5,043 ($79.13 per kBtu/hr.) Typical gas heating installation.	• $2,656 (40 kBtu/hr. unit) • $2,968 (120 kBtu/hr.)
Geothermal Heat Pump (GSHP)	• $9,770 per ton (median 4-tons) • $38,656 median cost	• $7,420 per ton (19.4 EER, COP 3.8 low-k soil std grout) • $25,780 for a 4-ton unit
Cooling	• $1,977 per ton • $5,930 median cost	• $3,704 per ton unit (SEER 18 replacement) • $4,712 per 3-ton unit
Thermostat	• $167 programable thermostat • $236 connected thermostat	• $170 programmable thermostat
Mechanical Ventilation	• $725 (local exhaust fan) • $804 (dwelling exhaust) • $2,473 (ERV, n=5) • $3,197 (HRV, n=6)	• $360 (exhaust or supply fan) • $850 (CFIS) • $1,480 (50 cfm 70% HRV) • $1,540 (50 cfm 70% ERV)
INSULATION		
Attic Framed Floor	• $2.88 per ft² (blown cellulose) • $1.46 to $1.79 (other insulation types “unknown” and “blown”)	• $1.90 per ft² (R38 blown cellulose)
Attic Sloped Roof	• $8.32 per ft² (ccSPF) • $6.40-$7.04 per ft² (other insulation types)	• $4.36 per ft² (R30 ccSPF)
Wall Cavity Insulation	• $2.24 per ft², $1.70-$2.53 per ft² (depending on the insulation type)	• $2.20 per ft², from $1.40-$2.90 (R13 cellulose into previously uninsulated walls)
Exterior Wall Insulation	• $9.36 per ft² (n=4) • From DER literature review: • $4.94-$15 per ft² (insulation only). • $6.10-$8.50 per ft² (exterior finish) • $13.10-$23.05 per ft² (insulation with cladding/finish)	• $1.50 per ft² (R12 polyiso wall sheathing insulation) • $4.00 per ft² (installation new fiber cement siding)
Foundation Framed Floor	• $8.53 per ft² (ccSPF) • $3.32 per ft² (cellulose)	• $3.10 per ft² (crawlspace, R30 ccSPF) • $2.30 per ft² (basement, R30 ccSPF) • $1.10 per ft² (R30 fiberglass batt)
Basement Walls (Half Height)	• $5.73 per ft² (polyiso) • $4.46 per ft² (ccSPF) • $6.10 per ft² rim joist (ccSPF)	• $2.50 per ft² (basement walls) • $1.60 per ft² rim joist (R12 polyiso)
AIR SEALING		
Air Sealing	• $0.34 per ft² of floor area(20%) • $0.54 per ft² (40%) • $0.68 per ft² (60%)	• $1.20 per ft² (33% reduction) • $2.20 per ft² (66% reduction) • $2.80 per ft² (87% reduction)
LIGHTING		
Lighting	• $6.88 per bulb (LEDs) • $7.81 per bulb (CFLs)	• $4.80 per 800 lumen LED ($0.006 per lumen) • $1.84 per 800 lumen CFL ($0.0023 per lumen)
WINDOWS		
Windows	• $626.37 per window replaced. (Not enough data to normalize by window surface area. But if a typical window is 4’x4’, then $626.37/16ft²= $39 per ft².	• $39-$49 per ft² of window (depending on the type of 2x glazed, argon units installed)
APPLIANCES		
Refrigerator	• $1,092	• $1,000-$1,400 (depending on efficiency)
Dishwasher	• $643	• $750-$1,000 (depending on size and efficiency)
Washing Machine	• $1,791	• $970-$1,400 (front load) • $690-$970 (top load)
Clothes Dryer	• $1,966	• $760 (electric dryer) • $1,000 (gas dryer)

[14] https://remdb.nrel.gov/index.php

Across most upgrade measures, the costs in the NREL EMDB are lower than those reported for projects in the deep retrofit database. In many cases, by substantial fractions, ranging from 25 to >50% lower. We show some notable examples of differences in typical measure costs in Figure 36. The only notable exception is envelope air sealing, where the NREL data suggest higher costs than reported in the DER database. Some measure costs are similar between the two sources, including 50-gallon heat pump water heaters, programmable thermostats, wall cavity insulation, attic framed floor insulation (depending on the type of insulation), refrigerators and windows.

Costs in the NREL EMDB may be lower for a number of reasons.

- First, most of the measure costs were based on data gathered by NREL and its partners in the period from roughly 2005 to 2010, and there are no mechanisms in the database or analysis tools to adjust these costs to the current value of the US dollar. Relative to the year 2019 (which is the assumption used for all LBNL DER costs reported in this report), RSmeans historical cost adjustments suggest that 2010 dollars can be converted to 2019 dollars by multiplying by 1.266 (1.532 for 2005 costs). By this logic, if the $2,200 80-gallon heat pump water heater cost was recorded in 2010, it would be adjusted to $2,785 in 2019 USD$, which is still much lower than reported in the LBNL data ($3,828). Adjusting for inflation gets many measure costs closer to one another, but by no means comparable.
- Second, costs may be lower in the NREL database due to different data sources. The origins of NREL measure data are not clear, but they may include highly cost-constrained sectors, such as low-cost weatherization. Similarly, there may be cost differences between typical or standard practice (NREL data), compared with more comprehensive deep upgrade projects (LBNL data). Deep retrofit contractors or programs may have higher overhead and project management costs, and they might also perform more robust work (e.g., diagnostics, commissioning, HVAC sizing, etc.).

7. Project Characterization

Table 14 summarizes the project characteristics. Many projects did not report some or all of these characteristics, so the tabulated values do not always add up to the total number of projects. The 1,739 projects were distributed (unevenly) over 15 states (see Figure 6). Most of the projects (76.7%) were single-family detached buildings, followed by manufactured homes (16.4%), and single-family attached buildings (4.3%). The median conditioned floor area was 1,768 ft^2 (mean of 1,989 ft^2). Only 6 projects indicated a change in floor area during the renovation work, indicating that changes in floor area are uncommon in the homes in this study. This contrasts with a prior review of energy upgrade projects by (Less & Walker, 2014), which showed that 24% of the projects reviewed increased floor area (by an average of 670 ft^2). The homes cover a range of vintages. Compared to the US housing stock, homes built between 1960-1980 are overrepresented and pre-1900 and post-2000 homes are under-represented. A substantial number of homes were built in the last 20 years showing that there is scope for home performance upgrades even in relatively new construction. The vast majority pf projects were recent: 84% of the projects were from 2018-2020.

Table 14. Summary of project characteristics.

	PROJECT CHARACTERISTICS	NUMBER OF HOMES REPORTING
Construction Type	Wood Frame	399
	Concrete Masonry Unit	47
	Unknown	1,293
Number of Stories	1	344
	2	254
	3	24
	1.5	45
	2.5	24
	Unknown	1,048
Number of Bedrooms	2	68
	3	316
	4	145
	Unknown	1,210
Bathrooms	1	31
	2	104
	3	27
	Unknown	1,577
Foundation Type	Basement	316
	Slab	75
	Crawlspace	34
	Crawlspace and Basement	63
	Slab and Basement	51
	Unknown	1,200
Project Duration	1 month	855
	2 months	258
	3 months	110
	4 months	63
	5 months	31
	6 months	23
	>6 months	70
	Unknown	329
Project Year	2020	828
	2019	374
	2018	258
	2010-2018	279
Home Vintage	Pre 1900	59
	1900-1960	274
	1960-1980	728
	1980-2000	476
	2000-2020	114
	Unknown	88

APPENDIX E – Project Characterization has more details on project characterization. The appendix also has tabular breakdowns project counts, floor area, cost and incentives broken down by Climate Zone, Retrofit Type, Energy Program Participation, and Vintage.

7.1 Project Costs and Incentives

Unless otherwise stated, project costs discussed in this report are gross project costs (i.e., not including any incentives or rebates) and are adjusted to represent 2019 US dollars ($) and are adjusted to be representative of national average costs (see details in Section 2.4). The median total gross project cost recorded in the database was $8,740 (mean of $14,329). The distribution of total gross project costs is shown in Figure 37 (see APPENDIX E – Project Characterization for distribution of project costs per ft^2). The 95th percentile total gross project was $46,765, with a small subset of projects in the $50,000 - >$100,000 range. Many of the projects included only one or two measures. When projects are filtered to include a minimum of three measures, the number of projects is reduced to 921 and the median project cost increases to $10,470 (mean of $19,000). The median cost per ft^2 is $4.95ft^2 (mean of $7.40/ft^2). When filtering to include only projects with three or more measures, the floor area normalized costs increase to a median of $6.27/ft^2 (mean of $9.28/ft^2). Project costs varied substantially by climate zone and energy program, but these trends only reflect the nature of the programs that contributed data, they do not necessarily represent any underlying trends in retrofit activity.

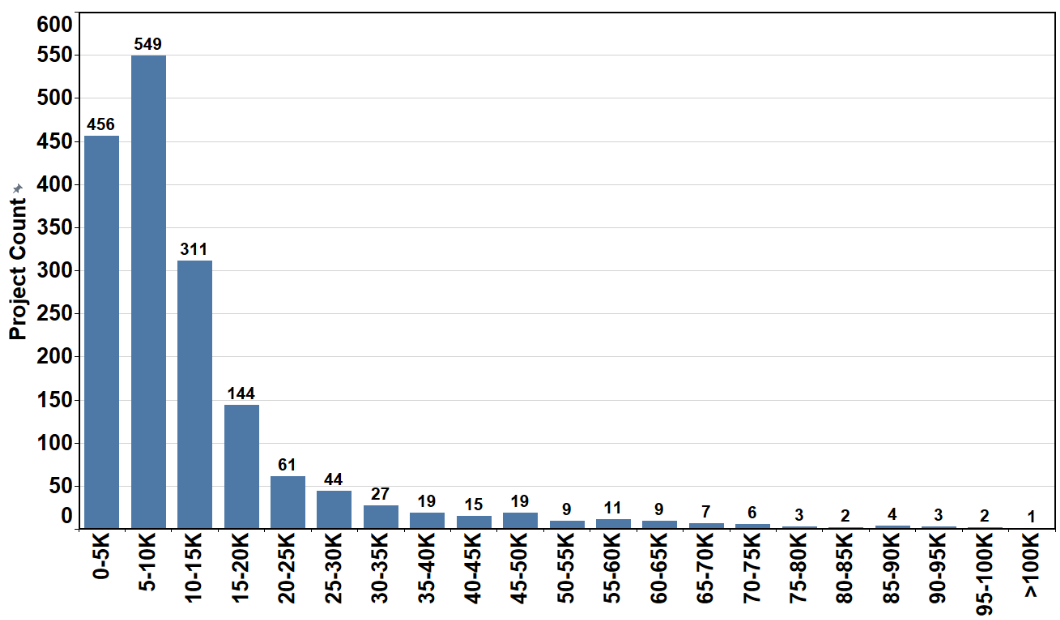


Figure 37. Distribution of gross project costs ($).

71% of projects reported some rebates. Many projects included more than one rebate measure, and when added up at the project level, the median total rebate was $1,327 (mean of $3,053), or 21% of the total gross project costs (mean of 30%). The median net-project cost (including rebates) was $7,450 (mean of $12,171). Projects with three or more measures had net-costs of $9,573 (mean $16,756). The vast majority of rebates were recorded at the whole-house level, with a substantial fraction also recording rebates in HVAC and Attic sections. Electrical rebates for PV systems were by far the largest, with a median rebate of $3,791. This reflects the substantial federal and local incentives for PV over the last decade along with the high cost of these systems.

Many of the most common measures are those with the best energy savings for their cost (i.e., they are cost-effective). These are also the measures most likely to have rebates or tax-breaks associated with them. From discussions with contractors (as illustrated in the related industry survey (Chan et al., 2021)), it is clear that these financial incentives bring contractors and businesses to the home remodel market. They are a key driver for selling retrofits, because people like to “get a deal” when making purchasing decisions.

7.2 Climate Zone

Most projects were recorded in climate zone (CZ) 3C, 4A, 5A, and 3B. Much smaller but still substantial numbers of projects were recorded in CZ 6A and in 2A. Consistent with this, the state with the most projects recorded in the database is California with a total of 847 (CZ 3B and C), followed by Massachusetts with a total of 366 (CZ 5A). It is important to note that these do not necessarily reflect whole home energy upgrade activities across US climate zones, it simply shows where project data was available for assembling the database.

With a focus on the regions with the most project data, the projects in cold climates (5A and 6A) are generally more expensive than those in milder climates (3B, 3C and 4A), both in terms of total gross costs and floor area normalized costs. For example, floor area normalized costs recorded in the database are roughly $7.00/ft^2 in cold regions compared with $3.00/ft^2 in milder locations. These are not projects that necessarily achieved the same energy performance, so this is not an apples-to-apples comparison. Instead, this shows that more money was spent on cold climate projects, generally because their energy use is higher justifying this greater investment. Dwelling floor area was also higher on average in the cold climate locations, typically roughly 2,100 ft^2 vs. 1,600-1,800 ft^2. Total incentives and incentive fractions were by far the greatest in Climate Zone 5A, with otherwise similar incentive rates in CZ 3B, 3C and 6A. These are almost entirely driven by the incentive rates selected by program operators located in those climate regions (see Section 7.4).

7.3 Retrofit Type

Retrofit Type was a category entered for most projects that generally characterized the nature, scope and focus of the project. Examples of retrofit types include Electrification, Superinsulation, Envelope-Focused, etc. By far the most common retrofit type was “Home performance upgrade” (n=1,061), which represents a project whose measures target both equipment and building envelope with equal emphasis, and whose methods and materials are fairly standard and off-the-shelf. Other common retrofit types were Electrification (n=294), Individual measure (n=251), HVAC-focused (n=226), and Envelope-focused (n=122), with more than 100 projects in each of these categories. Consistent with findings from the literature review (Less et al., 2021), very few projects were recorded pursuing superinsulation strategies (e.g., Passive House) (n=8). Again, the retrofit types are in-part dependent on the programs that contributed data to the database and do not necessarily represent all patterns/trends in US upgrades.

Many electrification projects included PV panels, which is a potential driver behind some of the higher normalized costs (\$9.61 per ft^2 compared with \$3-5 per ft^2 for other commonly recorded retrofit types). Incentive fractions were typically very high in the envelope-focused project (60%), while HVAC-focused and Electrification projects had 29 and 25% incentive fractions, respectively. It is notable that while Electrification work is a newly emerging trend, with unfamiliar technologies for many contractors and homeowners, the incentives were not particularly high when averaged across all Electrification projects. The large amounts of electrification projects in MA and VT are due to programs operating in those locations with decarbonization goals, including *MA DOER – Home MVP* and *Zero Energy Now* (see Section 7.4). These two programs offered higher incentive rates.

7.4 Energy Program Participation

All but 34 of the projects participated in an energy program, Table 15. Much of the of project data came from whole home retrofit programs, and some of the trends and patterns are the result of that sample of convenience. The program with the highest median total project cost is *VT New Leaf Design - Zero Energy Now*, that was entirely comprised of whole home aggressive upgrade projects targeting >50% fossil fuel savings, using electrification strategies. Projects participating in Building America research efforts had the next highest project costs, and these are also projects with comprehensive scopes and fairly aggressive energy targets. TN/NC - EEtility PAYS is notable as a Pay-As-You-Save program, which leverages larger numbers of projects with fixed contractor networks and streamlined work scopes that overall reduce project costs for fairly comprehensive upgrades. Many of the CA MTC - BayREN Home+ projects include only single-measure HVAC work. The CEE programs focus on gas savings, and projects are generally multi-faceted, including both envelope and HVAC upgrades. CEE is notable for having a fixed network of contractors who provide all work for the program at pre-agreed upon costs. This reduces measure costs and it leverages the program staff for project recruitment and development of work scopes. This means these projects are reasonably comprehensive, while maintaining low costs.

The highest median incentive fractions were provided by programs encouraging home electrification, including *MA DOER – Home MVP* (37%) and *Zero Energy Now* (24%). The higher incentive rates suggest that this work requires greater encouragement for both contractor and homeowner participation, largely due to unfamiliarity with technology, supply chain issues and the like. All other programs fell into the range of 14-18% typical incentive fractions.

Table 15. Energy program summary per number of projects.

ENERGY PROGRAM	Number of Projects	Median Conditioned Floor Area (ft²)	Median Gross Project Cost ($/ft²)	Median Gross Project Cost ($)	Median Project Incentive ($)	Median Incentive Fraction (%)
CA MTC - BayREN Home+	**700**	**1,757 (n=691)**	**$2.84 (n=691)**	**$5,336 (n=700)**	**$841 (n=700)**	**13.6% (n=700)**
MA DOER – Home MVP	**362**	**2,078 (n=362)**	**$6.84 (n=362)**	**$13,540 (n=362)**	**$4,972 (n=362)**	**37.4% (n=362)**
TN/NC - EEtility PAYS	**332**	**1,600 (n=332)**	**$5.60 (n=332)**	**$9,262 (n=332)**	**---**	**---**
U.S. DOE - Building America Research	77	1,387 (n=77)	$14.25 (n=77)	$21,751 (n=77)	$22,758 (n=1)	14.4% (n=1)
CA Program A	63	2,335 (n=1)	$5.31 (n=1)	$14,477 (n=63)	$2,953 (n=34)	16.3% (n=34)
CA CPUC - Energy Upgrade CA	54	1,768 (n=47)	$6.70 (n=47)	$11,438 (n=54)	$2,386 (n=30)	18% (n=30)
MN CEE - Program A	52	2,192 (n=52)	$3.52 (n=52)	$8,420 (n=52)	$1,135 (n=52)	13.9% (n=52)
VT New Leaf Design - Zero Energy Now	35	1,982 (n=33)	$28.35 (n=33)	$53,369 (n=35)	$14,608 (n=32)	24.3% (n=32)
GA Southface - GoodUse	15	5,391 (n=14)	$17.61 (n=14)	$67,219 (n=15)	---	---
NY NYSERDA - Deep Retrofit Pilots	8	1,602 (n=8)	$65.59 (n=8)	$124,197 (n=8)	---	---
USA ACI - Thousand Home Challenge	6	1,619 (n=6)	$46.52 (n=6)	$63,360 (n=6)	$1,596 (n=1)	5.9% (n=1)
CA HEA - HomeIntel	1	1,604 (n=1)	---	---	---	---
None	1	1,400 (n=1)	---	$26,050 (n=1)	---	---
No Response	33	(n=114)	(n=116)	(n=34)	(n=521)	(n=521)

8. Energy Performance

Energy performance was reported only for a subset of the projects recorded in the database (1,239 out of 1,739 total projects). The energy savings data was predominantly modeled or deemed, with very little actual energy savings verified by utility bills. For example, net-site savings was reported by 1,185 projects, largely made up of modeled (66%) and deemed (28%) savings, with small fractions of actual (5%) and unknown data types. The pre-retrofit data had a much higher fraction of projects reporting actual energy use (46% vs. 54% modeled). Many of those reporting actual pre-retrofit data contributed estimates of modeled savings. Some models were calibrated using the actual consumption (e.g., for the TN/NC - EEtility PAYS program), while others were not. More details on reported energy performance are given in APPENDIX F – Energy Performance.

8.1 Energy Use and Savings Distributions

Distributions of energy savings for each of the key metrics across all the homes in the database are shown in Figure 38 (floor area normalized values in Figure 39). In these and subsequent figures, "n" is the total number of projects summarized in the figure and the values vary depending on data availability. Median project savings for net-site energy, energy cost and carbon emissions were 6,961 kWh (3.92 kWh/ft^2), $467 ($0.26/ft^2), and 3,473 lbs. CO_2e (1.85 lbs. CO_2e/ft^2), respectively. These figures illustrate the substantial variation in energy savings, as to be expected given the large variability in home size, occupancy, construction, climate and the retrofits that were performed. However, these median values give some idea of the magnitude of savings these projects achieved. Additional distribution plots of pre- and post-usage along with energy savings are provided in APPENDIX F – Energy Performance.

Percent savings distributions were quite consistent across each of the three-energy metrics, with 28% median savings for carbon and energy cost, and 33% median net-site energy savings. For each metric, the maximum apparent savings were around 80%, though 14-25 projects saved >80% for each energy metric. For comparison, a past meta-analysis of US deep retrofit projects (Less & Walker, 2014) found higher median site energy and cost savings (47% and $1,283, respectively), suggesting that projects were on average less aggressive in this database compared with the 2014 review. This is also evidenced by comparing the total project costs, which were typically $40,420 in the prior review, while being substantially less across the current database (see Section 7.1).

In Figure 40 we compare the distribution of energy cost savings for the 273 Electrification projects with cost savings data, against the savings for all other retrofit types. The tendency for Electrification projects to increase post-retrofit energy costs in some projects is evident in comparing the distributions, by as much as $1,000 per year in some cases. But we also observe that many Electrification projects achieved high reductions in annual energy cost. This is most likely in homes with high pre-retrofit energy bills, such as those that heat with propane or fuel oil. We also confirm that the increase in energy costs in some Electrification projects are the result of increases in electricity consumption paired with high regional electricity rates. Notably, many of the regions with programs encouraging Electrification have high electricity rates that make the economics less desirable, including Massachusetts ($0.184 per kWh), California ($0.169 per kWh), Vermont ($0.154 per kWh) and New York ($0.143 per kWh).

The results below combined electric and natural gas use into singular net-site energy values. If we look at the fuels separately, the mean electricity savings in kWh per site project 1,271 kWh and the median is about 298 (n=995). For natural gas, the mean savings are 12,945 kWh with a median of 6,228 kWh (n=732). The mean CO_2 savings was 5,056 lbs. CO_2 (2.79 lbs. CO_2 /ft^2) with a median of 3,476 lbs. (1.85 lbs. CO_2 /ft^2).

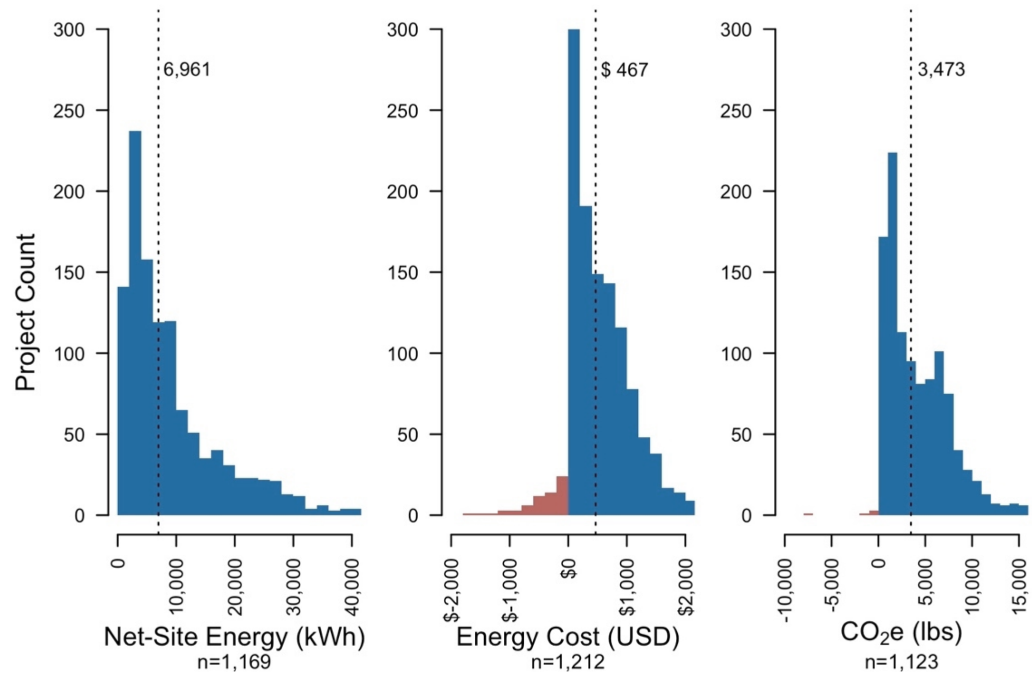


Figure 38. Annual energy savings distributions for each energy metric.

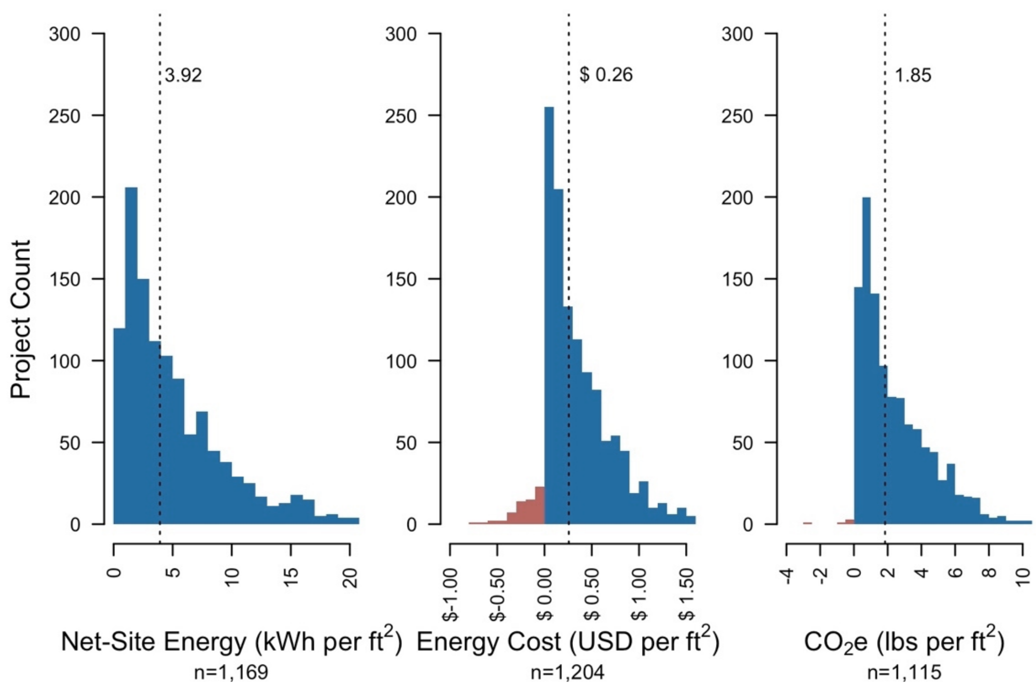


Figure 39. Annual energy savings per ft^2 distributions for each energy metric.

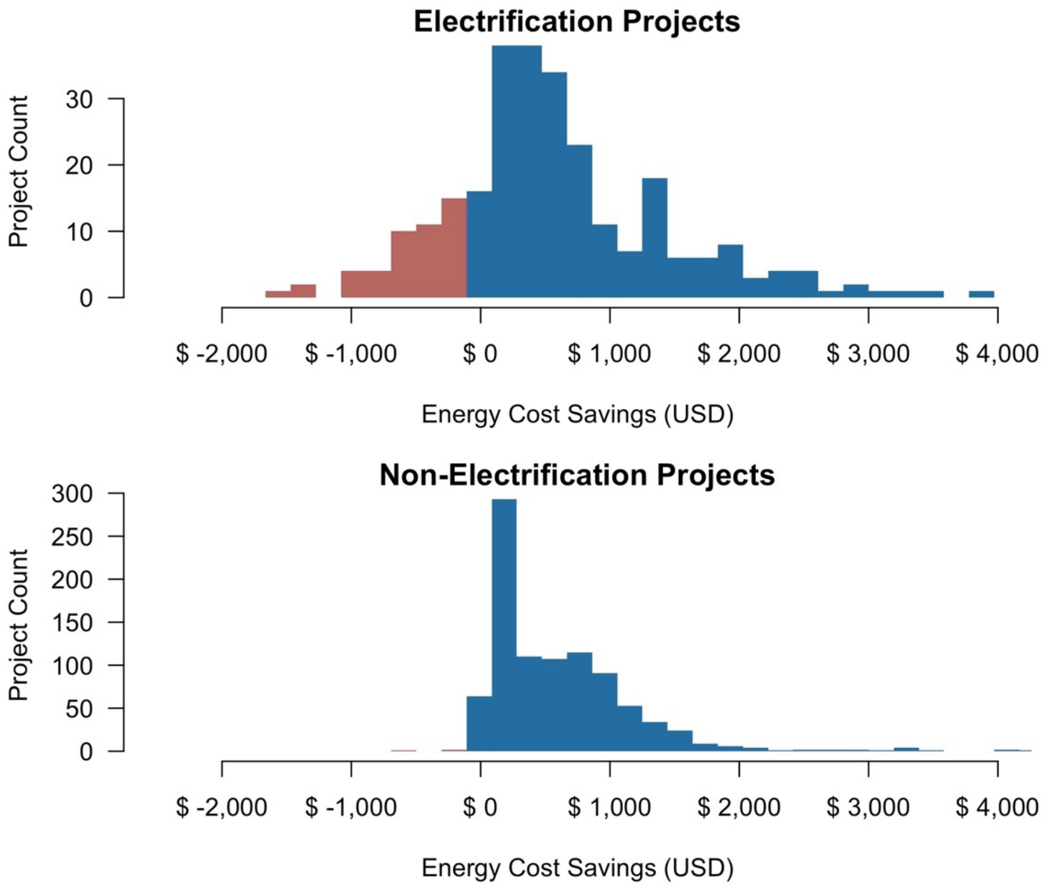


Figure 40. Comparison of energy cost savings distributions for Electrification and non-electrification projects.

8.2 Regression Modeling of Energy and Carbon Savings

If we want to optimize how home energy upgrades are performed, we need to determine which project features most reliably lead to energy/carbon savings. To do this, we used a regression analysis. Random forest regression models were built to predict the percent net-site energy savings and the carbon emissions reductions for each project, based on the project features (e.g., floor area, vintage, retrofit type, building type, etc.), as well as the dollars recorded in each combination of section-action-component (e.g., USD value recorded for HVAC_Install_Heat pump). The cross-validated (10-fold, repeated 5-times) prediction root mean squared errors (RMSE) averaged 12.2% (adjusted R2 0.578) for the net-site energy model and were 15.0% (adjusted R^2 0.437) for the carbon savings model. These models suggest that typical errors for predicting savings for projects that were not used in building the regression models were 10-15%, and that roughly half of the variance in the data is explained by the models.

The variable importance was extracted using a recursive feature elimination algorithm to identify which input variables had the strongest impact on the accuracy of the predictions. The scaled variable importance is shown for the net-site energy savings model in Figure 41 and for the carbon savings model in Figure 42. For both models, the strongest predictor variables were by far the total gross project costs (project_total_cost_gross), followed by the number of measures in the project (measureCount) indicating, not surprisingly, that the more effort and funds put into energy savings, the more energy is saved. When looking at individual measures, expenditures in the HVAC heat pump and PV system categories led to the greatest energy/carbon savings. Other common project expense categories amongst the highest ranked for predicting savings were wall insulation, water heater installation, attic framed floor insulation, envelope air sealing and lighting upgrades. Note that these results are not a cost-effectiveness assessment. Rather, they indicate what to invest in if you want to significantly reduce energy use/carbon emissions. This analysis also reveals some interesting correlations, such as investment in health and safety is more important than many other project features. It is unclear if there are health and safety measures that also save energy or is it that successful projects or programs include health and safety.

As project cost was the strongest predictor in both energy and CO_2 savings regression models, the correlation between total project costs per ft^2 and CO_2 and energy savings are shown in Figure 43 and Figure 44, respectively. These correlations show the clear and strong linear relationship between project costs per ft^2 and reported energy savings in the database. Both of these plots suggest that projects targeting >50% savings should be expected to spend roughly $30 per ft^2. Many fixed features of a home (vintage, construction type, stories) are relatively low in terms of correlation. This implies that the ability to save energy and carbon has far more to do with what is installed than what can't be changed about a house.

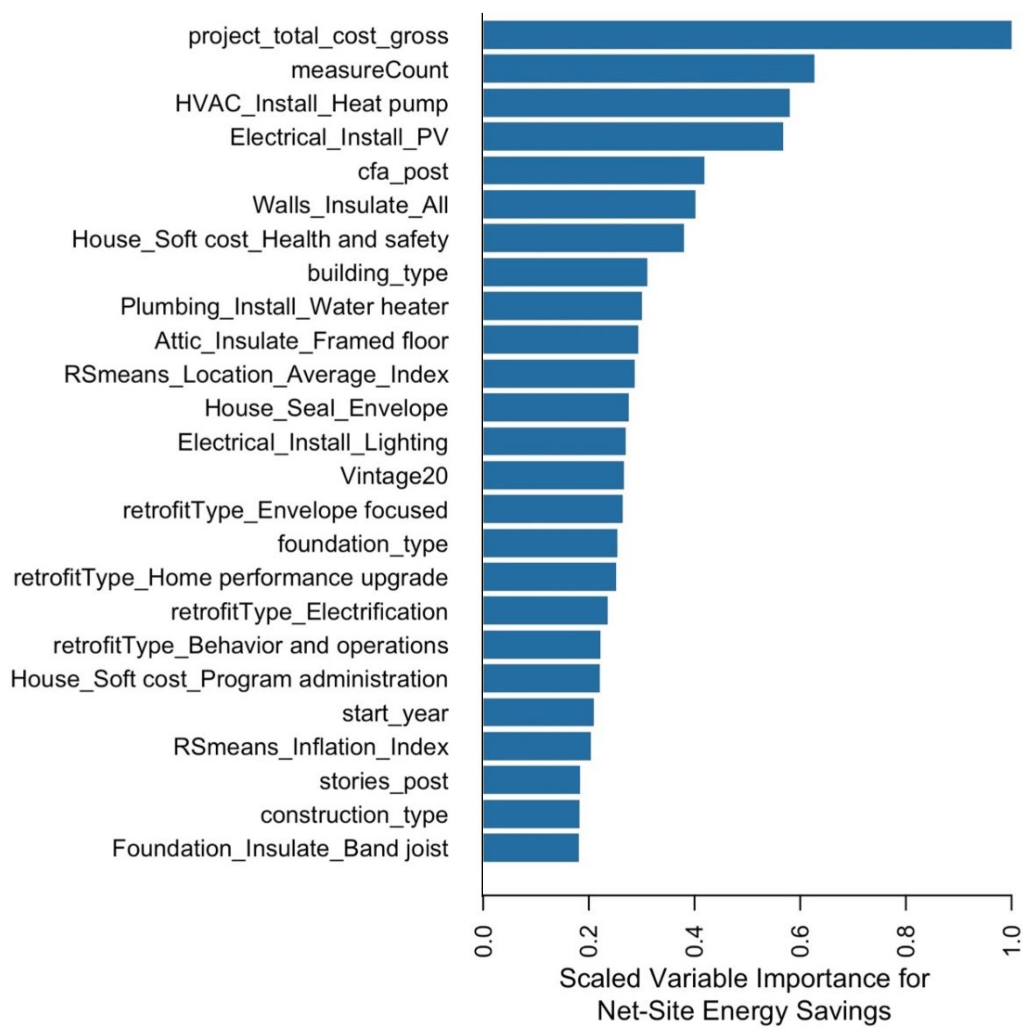


Figure 41. Net-site energy savings variable importance from recursive feature elimination using random forest regression model.

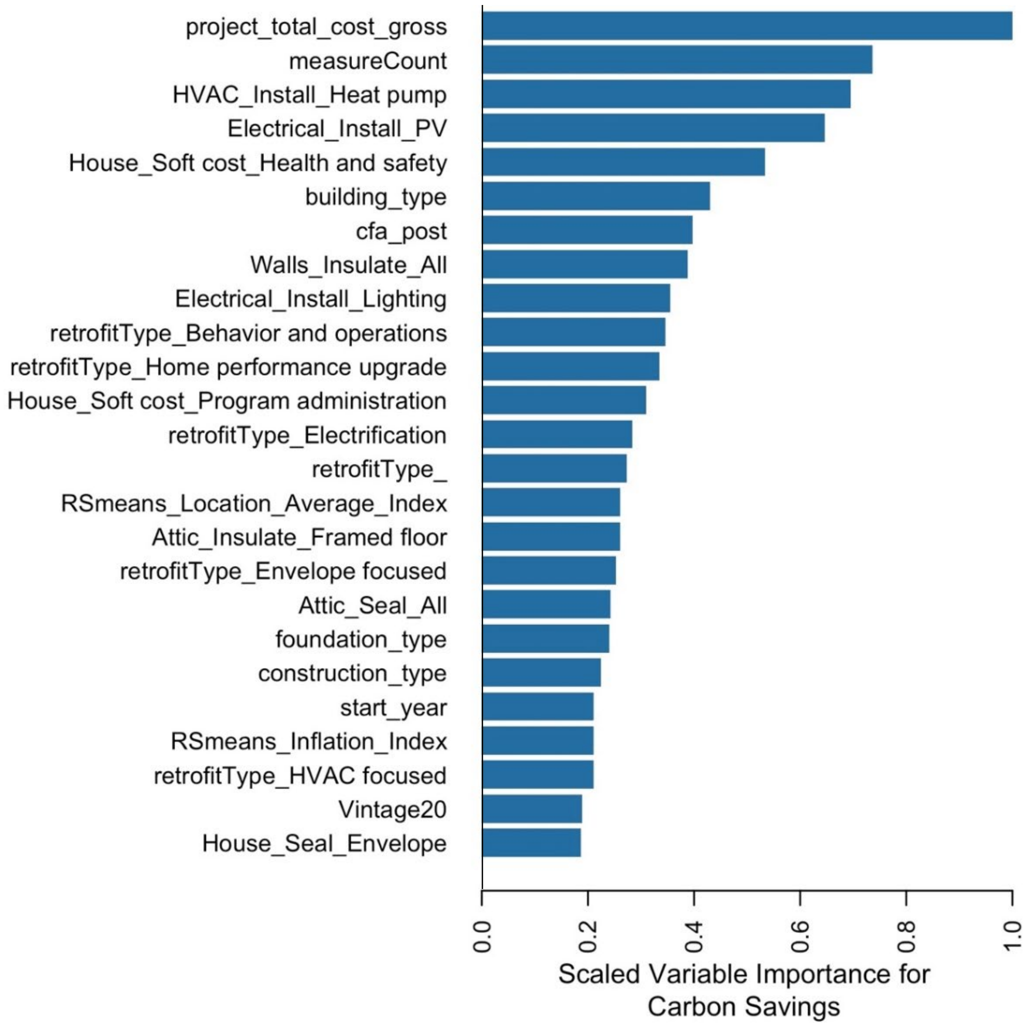


Figure 42. Carbon savings variable importance from recursive feature elimination using random forest regression model.

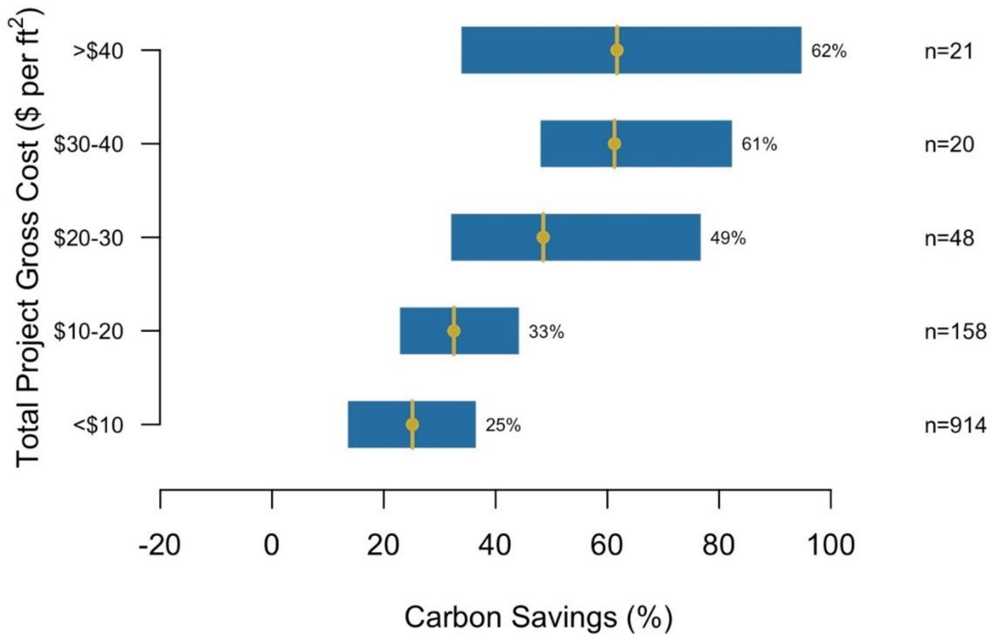


Figure 43. CO_2 savings dependence on gross project costs per ft^2.

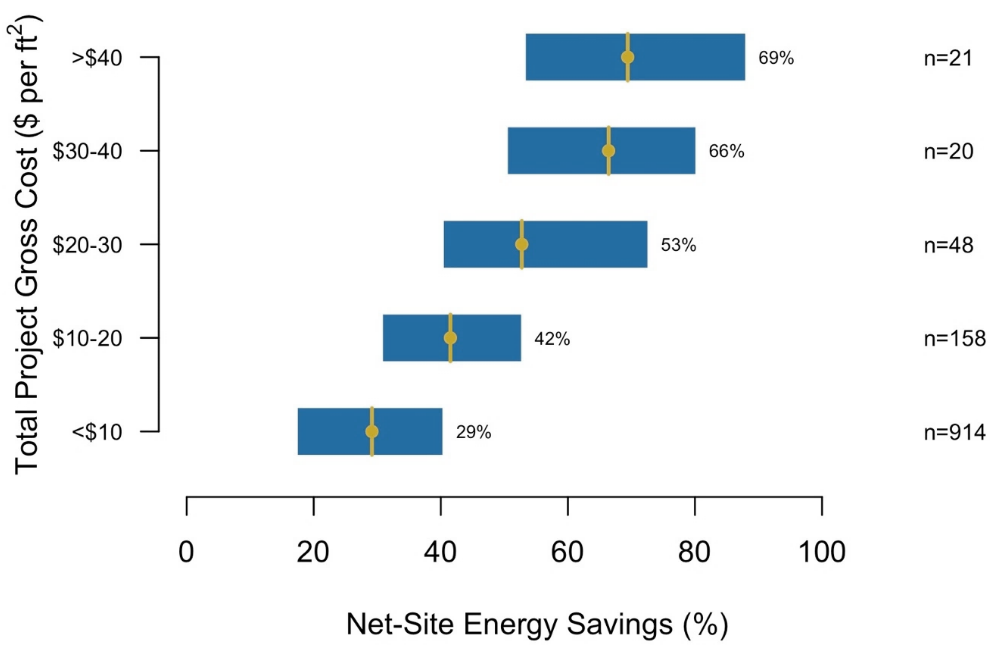


Figure 44. Net-site energy savings dependence on gross project costs per ft^2.

9. Measure / Component Energy Performance Specifications

Each measure was recorded along with its performance specifications (if available), such as equipment efficiency, insulation R-value, water heater energy factor, etc. We also compared the installed energy performance to *Energy Star, Consortium for Energy Efficiency (CEE)* tiers and new home building codes to determine if there is the capacity to do better from an energy standpoint, and also to see what performance levels are typically targeted compared to new construction. Distributions of recorded performance features are summarized in the following sections:

- HVAC performance features, Section 9.1.
- Water heating, Section 9.2.
- Air sealing, Section 9.3.
- Building envelope insulation, Section 9.4.
- Windows, Section 9.5.

Overall, high performance levels were not targeted in these home upgrades, because this was not the program intent. Until very recently, there was no impetus to aim for greater energy savings or CO_2 reductions. Notable exceptions for homes in this study were:

- **Heat Pumps:** The median heat pump installed met CEE tier 2 requirements (16 SEER, 12.5 EER and 9 HSPF (North and Canada 16 SEER, 11EER and 9.5 HSPF))
- **Furnaces:** Tended to be condensing AFUE 95/96
- **Water Heating:** The most common upgrade was to a heat pump water heater.

9.1 HVAC

HVAC equipment efficiency is shown for fuel-based heating equipment, heat pumps and cooling equipment in Figure 45. The heat pump and cooling system SEER ratings are shown in the top panels, while the heating efficiencies (HSPF and AFUE) are shown in the bottom panels. The current Energy Star performance criteria are shown as green dashed lines, while Consortium for Energy Efficiency (CEE) performance tiers 1-3 are shown as blue, orange and purple lines. The number of measures meeting the performance criteria are also listed in Table 16. Heat pump and cooling system efficiency ratings were generally compliant with Energy Star and CEE tier 1 requirements, but they were much less likely to meet or exceed CEE tier 2 or 3 criteria. Nearly all gas-fired heating equipment met Energy Star and tiers 1 and 2 of the CEE ratings, but equipment with AFUE >97 was rare.

Table 16. HVAC equipment compliance with Energy Star and CEE performance tiers.

System Type	Total Count	Energy Star	CEE Tier 1	CEE Tier 2	CEE Tier 3
Split Cooling SEER	123	99 (>=15)	87(>=16)	7 (>=18)	---
Heat Pump SEER	688	673 (>=15)	543 (>=16)	291 (>=18)	---
Heat Pump HSPF	668	650 (>=8.5)	650 (>=8.5)	386 (>=9.0)	334 (>=9.5)
Heating AFUE	511	479 (>=95)	486 (>=90)	479 (>=95)	6 (>97)

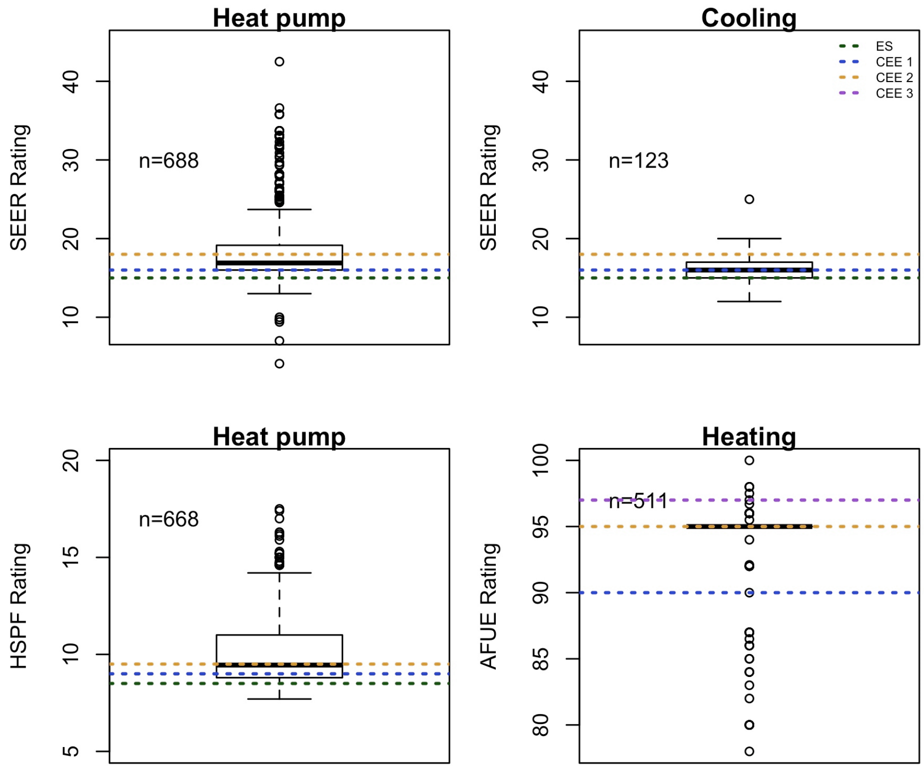


Figure 45. HVAC equipment installed efficiencies compared with Energy Star and Consortium for Energy Efficiency (CEE) performance tiers. Cooling is for systems that installed air conditioners only. Heating is for furnaces. Energy Star criteria for gas furnaces are AFUE of 90 and 95 in Southern and Northern regions, respectively. These are identical to the CEE 1 and 2 tiers.

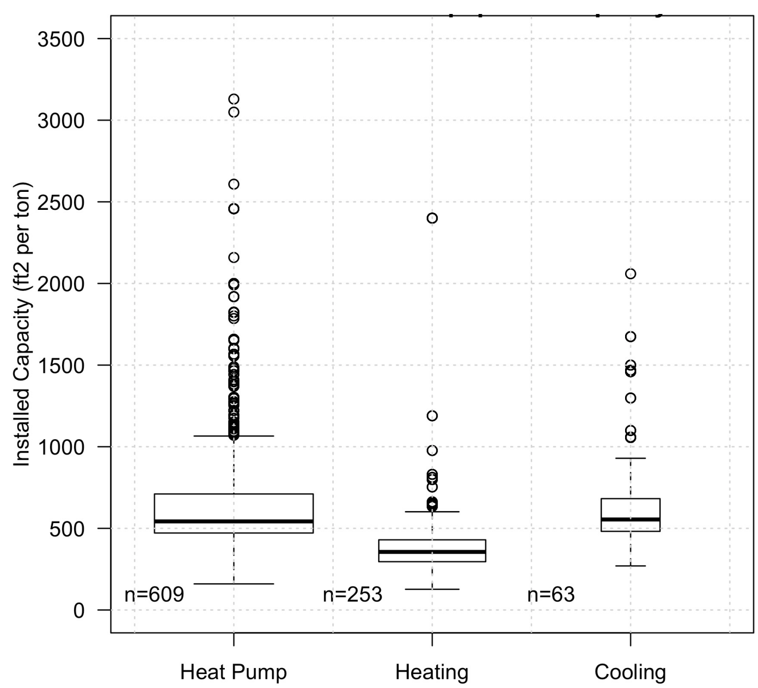


Figure 46. HVAC capacity by equipment type, floor area normalized.

HVAC sizing was disaggregated by HVAC system type in Figure 46, showing the ft² per ton of installed capacity per dwelling. System sizes were much larger for fuel-based heating equipment, with typical sizing at 356 ft² per ton, compared with 543 and 555 ft² per ton for heat pumps and cooling equipment, respectively. Notably, many heat pumps were being aggressively sized in the range of 500-1000+ ft² per ton, which most standard HVAC practice would consider under-sized. There are several possible explanations for these extreme sizing results: they were installed in super-efficient homes with low loads, they only served part of the house, more accurate load calculations are supporting smaller heat pump units, or that some units were installed with the express intention of not meeting the whole-dwelling load (e.g., if fuel-based equipment was left in-place). There are important compromises regarding heat pump sizing with the need to balance the extra cost per ton of heat pump capacity with the advantages of additional capacity in avoiding auxiliary strip heat operation at peak load.

9.2 Water Heating

Water heaters are rated according to their Energy Factor (EF), and distributions of EF recorded in the project database are shown for each water heater type in Figure 47. Electric heat pump water heaters have by far the highest EF, with a median value of 3.15, compared with all other water heating types below 1.0. The lowest EF values were recorded for storage tank heaters using fossil fuels, followed by tankless heaters and storage electric units. The difference in EF for heat pump units compared with gas tankless units is notable given that the typical installed cost of tankless gas hot water was more than $1,000 higher than for electric heat pump units (see Section 10.5). Energy Star criteria for Electric heat pump units is an EF >= 2.0 (for <55 gallons) and >=2.2 (for >55 gallons). The CEE criteria are identical to Energy Star for Tier 1, and they are 3.1 and 3.75 for Tier 2 and Advanced tiers. Effectively all heat pump water heaters recorded in the database met the Energy Star criteria and roughly half met the CEE Tier 2 requirement. For gas storage water heaters, the EF must be >= 0.67 and 0.77 for units less than or greater than 55-gallons, respectively. Gas tankless water heaters must have EF >= 0.90 (uniform EF >= 0.87), and while only four Tankless gas water heaters met the EF criteria, all met the Uniform Energy Factor (UEF) criteria.

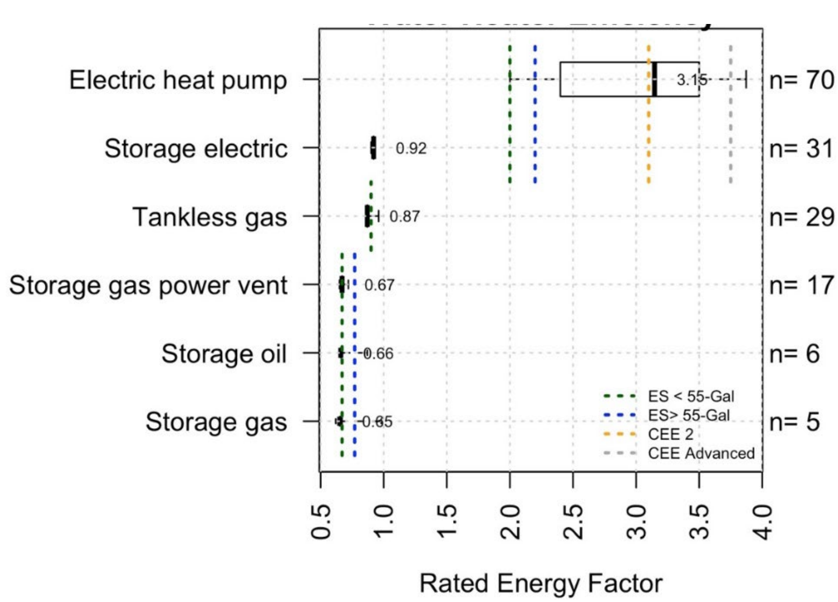


Figure 47. Water heater energy factors. Vertical dashed lines show Energy Star and CEE tier thresholds.

9.3 Air Sealing

Building envelope and duct air sealing have long been cornerstones of energy upgrade work in existing dwellings, and the projects entered in the database continued this trend. The percent reductions in building envelope and duct leakage reported for each project are summarized in Figure 48. Median percent reductions in leakage were much higher for ducts than for the building envelope (64 vs. 27%), while the typical costs for each measure were roughly similar at $789 (ducts) vs. $730 (building envelope) (see Section 10.2). The pre- and post-leakage measurements, along with the measured reductions in leakage are summarized for the building envelope in Figure 49 and for ducts in Figure 50.

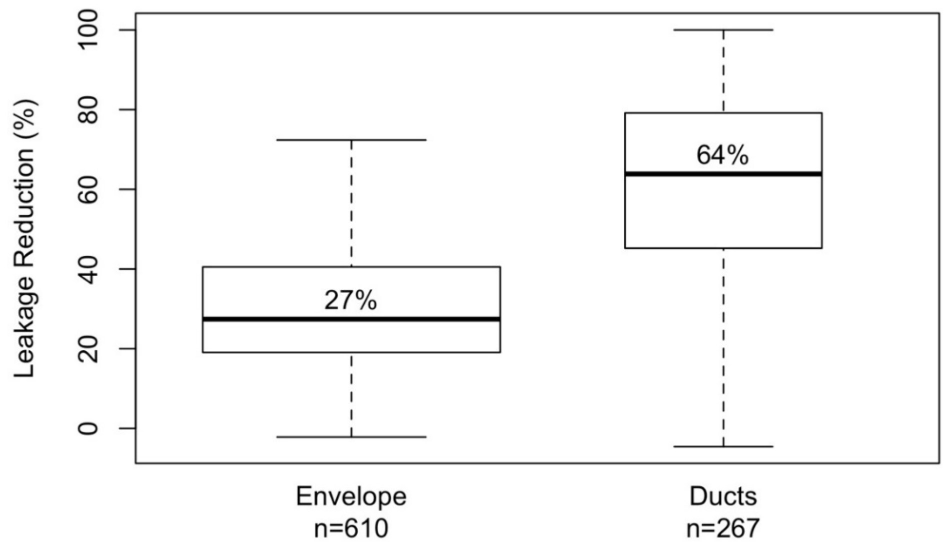


Figure 48. Building envelope and duct leakage reductions.

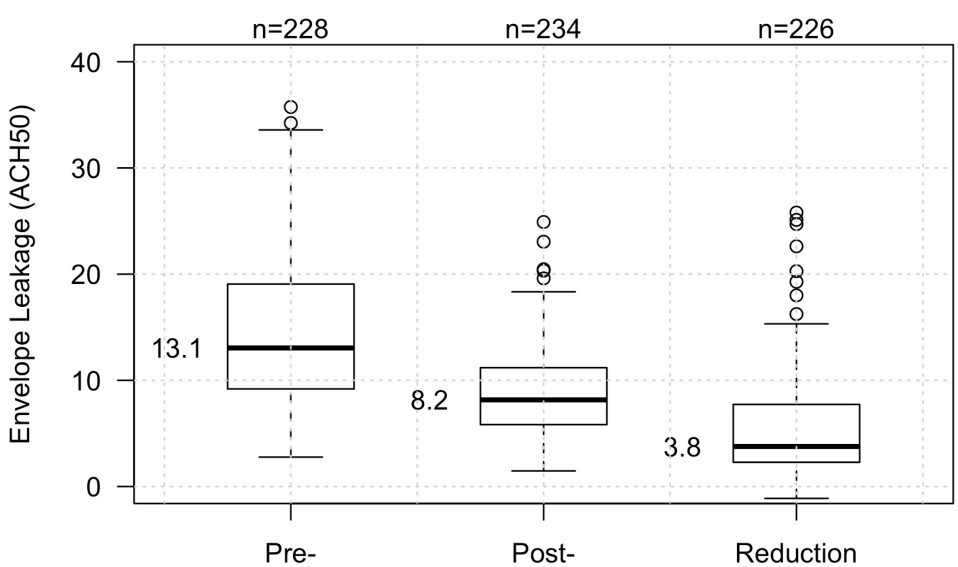


Figure 49. Building envelope leakage measures in upgrade dwellings, pre-, post- and reduction.

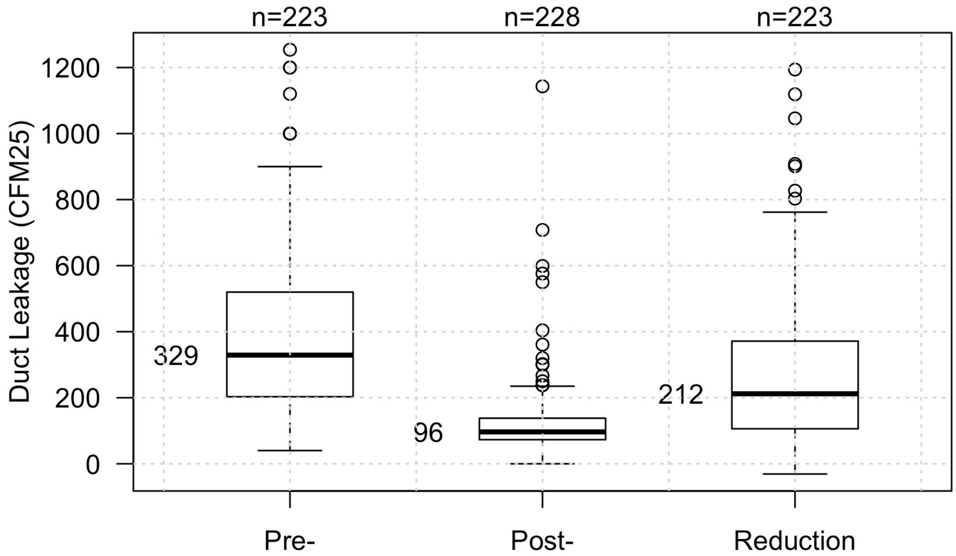


Figure 50. Duct leakage measures in upgrade dwellings, pre-, post- and reduction.

9.4 Building Envelope Thermal

Post-retrofit envelope R-value (ft^2-°F-hr./Btu) distributions are shown in Figure 51, sorted from the highest average R-value reported (Attic access) to the lowest (Foundation stem wall). All values with fewer than 10 entries have been removed from the plot.

Wall insulation values are notable. While most suggest filling of the wall framing with R-13 insulation, some projects show increased R-values >19, suggestive of exterior insulation or superinsulation approaches. While these strategies were the focus of much deep retrofit R&D in the early 2010's, our database shows very little activity on the super-insulation front. Of all projects that included wall insulation upgrades (n=265), only 5.7% included adding exterior insulation (n=15). Note: the counts in this text do not match those in Figure 51, because some measures did not report R-value, and some projects reported more than one measure in these categories (e.g., two different wall insulation line items). Similarly, the addition of roof deck insulation occurred in 123 projects (Attic_Roof) in plot below), and insulation was placed above the structural sheathing in 22% (n=27) of these roof insulation projects. Yet, compared with all projects that insulated the attic (either framed floor or roof), the addition of exterior roof deck insulation was extremely rare (3.2%). The installation of high-performance (R-5 or better) windows was somewhat more common, occurring in 14% of window upgrades (see Section 9.5).

The insulation levels of attic framed floor assemblies are summarized in in Table 17 and compared to (2018 IECC, 2017) code requirements (R-38 and R-49, depending on climate region). While the marginal costs of a few more inches of insulation are low, projects are clearly not targeting these insulation levels.

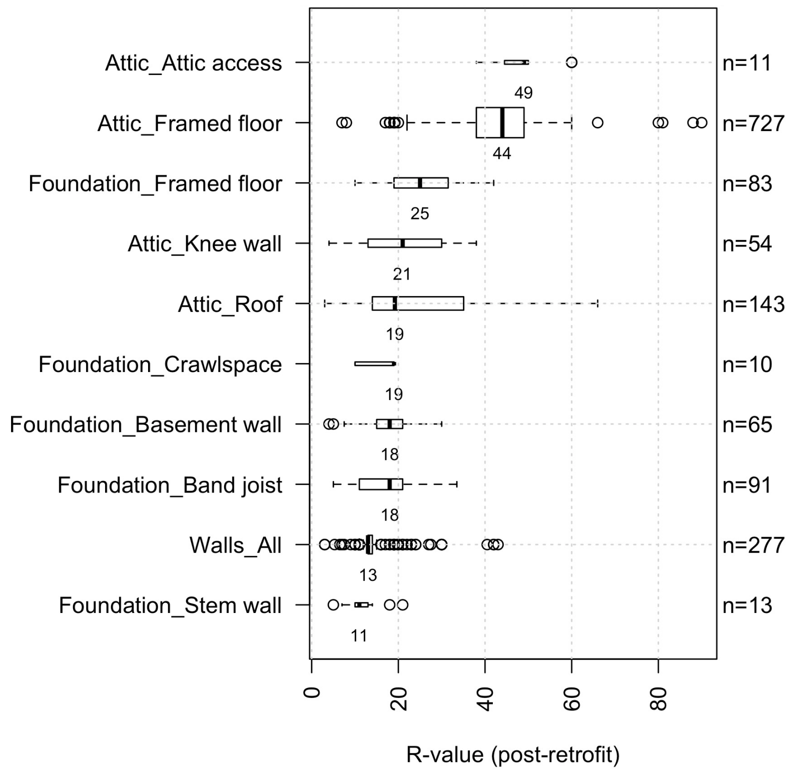


Figure 51. Post-retrofit R-value distributions for each building component.

Table 17. Attic framed floor insulation meeting or exceeding building code values.

Climate Zone	Count of Attic Framed Floors R-Values			Less than R-38
	R-38	R-49	R-60	
2A	35	0	0	18
3A	2	0	0	0
3B	10	8	0	0
3C	171	26	2	3
4A	117	0	1	0
4B	1	0	0	0
5A	4	90	23	8
6A	1	85	20	4
ALL	**422**	**209**	**46**	**34**

9.5 Windows

Window upgrade U-value and solar heat gain coefficient (SHGC) distributions are shown in Figure 52. Median values were 0.30 for both metrics. Window upgrades were relatively infrequent in the data set, with only 70 projects reporting them. The counts in Figure 52 do not equal 70, because some projects reported multiple window types with different SGHC or U-values in the same dwelling. The majority of window installations (n=41) occurred in projects located in Florida and were part of affordable housing upgrade efforts.

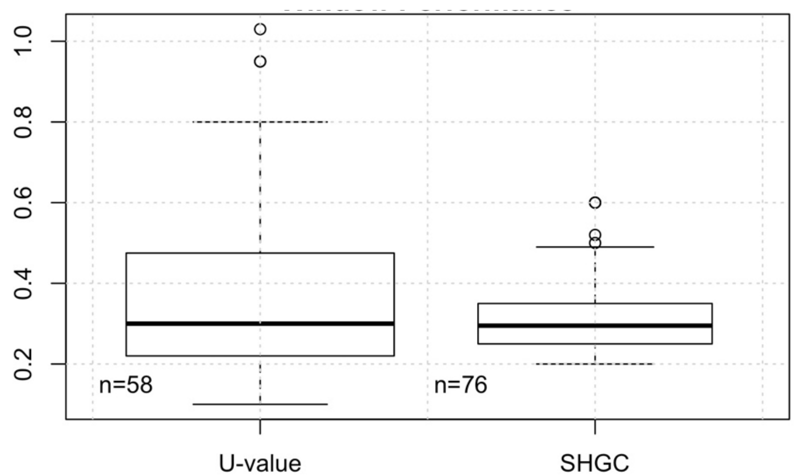


Figure 52. Window performance specifications.

The recorded performance values are compared against Energy Star window requirements in Table 18. The Energy Star requirements vary by climate region, and we could not match each recorded window installation against the Energy Star climate criteria. So, we assessed compliance of all window installations with all Energy Star criteria. Less than half of window installations met the U-value and SHGC requirements for Energy Star. Given that the majority of windows were installed in Florida, we focus on the "South" Energy Star requirements, where we see that nearly all windows met the U-value requirement of 0.4, while very few met the SHGC requirement of 0.25. Despite overall low performance, some projects installed very good windows, for example, 8 of 58 projects installed windows with U-values less than 0.2 (R-5). Finally, a single project reported window U-values of roughly 1, which is equivalent to a single-pane uninsulated window.

The moderately low performance features of retrofit windows were notable. We had previously reasoned that for those projects making large investments in window upgrades, they would likely opt for higher performance units, due to the lower additional marginal costs. A couple of possible explanations are worth noting. First, windows may have been replaced for non-energy reasons (e.g., existing windows damaged). Second, window installations may also have been restricted due to aesthetic requirements, or limitations of existing frames. Finally, projects may have sensed little marginal benefit from improved window performance, absent a legal/code requirement to meet the Energy Star requirements.

Table 18. Window performance data and comparison with Energy Star requirements.

System Type	Total Count	Energy Star South*	Energy Star South Central	Energy Star North Central	Energy Star North
U-value	58	55 (<=0.40)	28 (<=0.30)	28 (<=0.30)	27 (<=0.27)
SHGC	76	13 (<=0.25)	13 (<=0.25)	50 (<=0.40)	---

10. Measure / Component Costs

This section summarizes key measure costs from the deep retrofit database. APPENDIX G – Measure Costs gives more details.

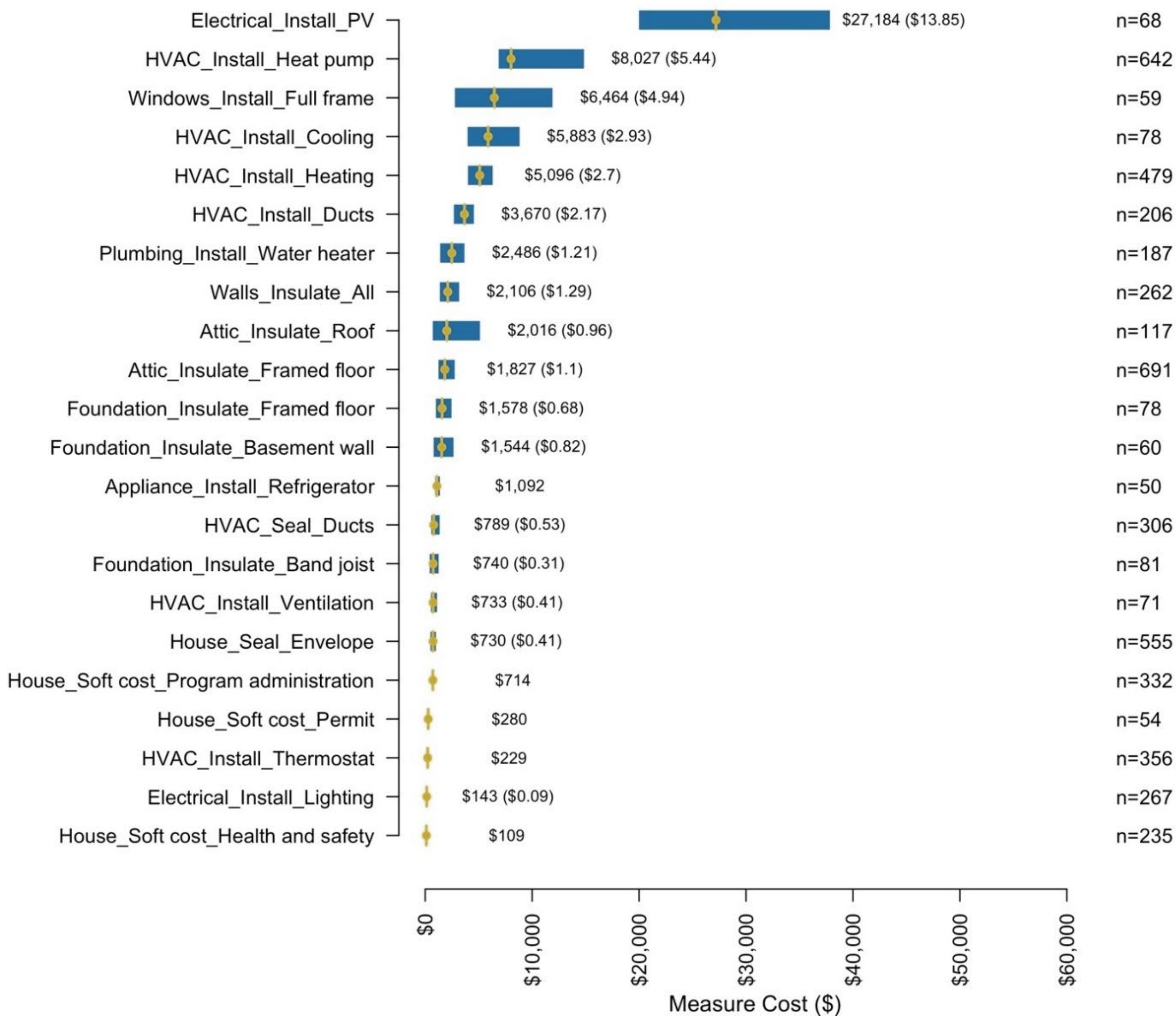


Figure 53. Most frequently reported measures sorted by total installed median cost.

The most frequently installed measures were identified as those with at least 50 entries with cost data. The cost distributions for those frequent measures are shown below sorted by median cost (Figure 53). Measure costs per ft^2 of dwelling floor area are shown in parentheses for each measure data label. Each measure is represented by the Section (what part of the house), Action (what was done) and Component (specific element or type addressed). The median value for each measure is marked by a yellow circle with vertical line, and the blue bar spans the range between the 25th and 75th percentiles. These figures show the range of costs between measures (e.g., attic insulation vs. envelope air sealing), while also showing the variability within each measure. The range of costs for almost all measures is very large – with interquartile ranges about half the mean value or more. This large range is indicative of how building condition, climate and other variables can dramatically alter the costs. This variability within measures has implications for business and homeowner risk acceptability. Measures that have better controlled costs (i.e., less variability) are likely to be more attractive due to reduced uncertainty. This implies that both cost reduction and cost control are important topics for future R&D efforts.

The frequent measures with median costs exceeding $5,000 per project were solar PV, HVAC equipment and window replacement. Mid-tier measure costs (from $1,000 to $4,000 per project) were identified for installation of HVAC ducts, water heaters, wall insulation, attic framed floor and roof insulation, foundation framed floor and basement wall insulation, and refrigerators. Lower cost measures ($50 to $1,000) included envelope and duct air sealing, band joist insulation and installation of mechanical ventilation. The lowest cost upgrades (<$250) were lighting and smart thermostats.

10.1 HVAC

Overall, 2,298 costed measures were recorded in the HVAC section. The most frequently recorded HVAC measures were: (1) heat pumps, (2) heating, (3) thermostats, and (4) ducts. Of these, heat pumps had the highest median costs, and traditional fuel-fired heating systems averaged $3,000 less than heat pump installations. Installation of mechanical ventilation and cooling equipment were recorded less frequently. Figure 54 summarizes the HVAC installation costs and shows the median values and ranges. The most frequently installed HVAC measures are discussed in greater detail below in Section 10.1.1 through Section 10.1.5. Note: the term "All" is used as a generic placeholder in these measure cost items to represent the situation where no information was available. For example, in Figure 54, "All_All" refers to any measure recorded in the HVAC category, where we do not know either the Action or the Component. This is represented as an HVAC cost, with no other detail. The "All_Ducts" category represents HVAC costs associated with the component Ducts, where we do not know the Action that was taken. For example, Ducts may have been installed, sealed, insulated, redesigned, etc.

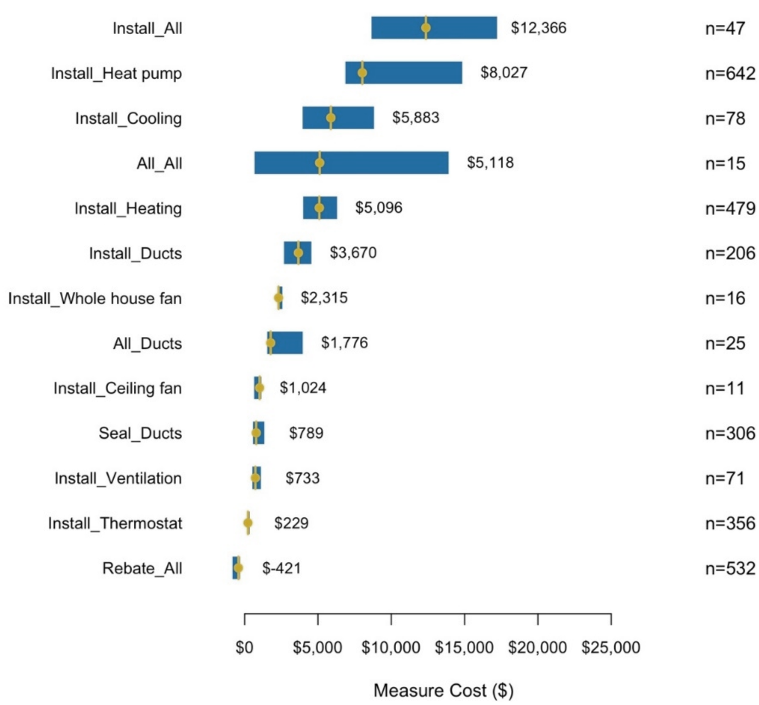


Figure 54. HVAC installation cost distributions.

10.1.1 Heat Pumps

A total of 642 heat pump installations were recorded in the database, with a median cost of $8,027. The median normalized costs were $5.44 per ft^2 and $3,387 per ton. Installation costs vary substantially by the type of heat pump installed, as shown in Figure 57. Ground source heat pumps were the most expensive, at nearly three times the total system cost of other ductless and ducted heat pump types. Ductless heat pump systems were more expensive than traditional air source heat pumps (ASHP), though they commonly had much higher heating and cooling efficiency. Regression analysis showed that the most important variables in determining heat pump cost include the capacity of the system (tons), the heat pump type (e.g., ductless mini-split vs. single-stage split heat pump), the home's floor area (cfa_post), the cooling and heating efficiencies (SEER and HSFP), Climate Zone, the Program the project participated in (program_participation), and the number of stories (stories_post). Less important variables included the location of the unit (location), the home vintage (vintage20), etc.

Ductless heat pump costs were also gathered as part of an energy upgrade literature review by (Less et al., 2021). The high-level summary is reproduced below in Figure 55, showing typical costs per ton for a basic installation, along with cost increases associated with different performance features (e.g., additional zones, improved efficiency). Error bars in Figure 55 show the typical range reported across sources in the literature, these are not standard deviations or other formal statistical measures. The median ductless heat pump cost gathered in this database was $4,397, which falls squarely within the range found in the literature ($3,957 to $5,464).

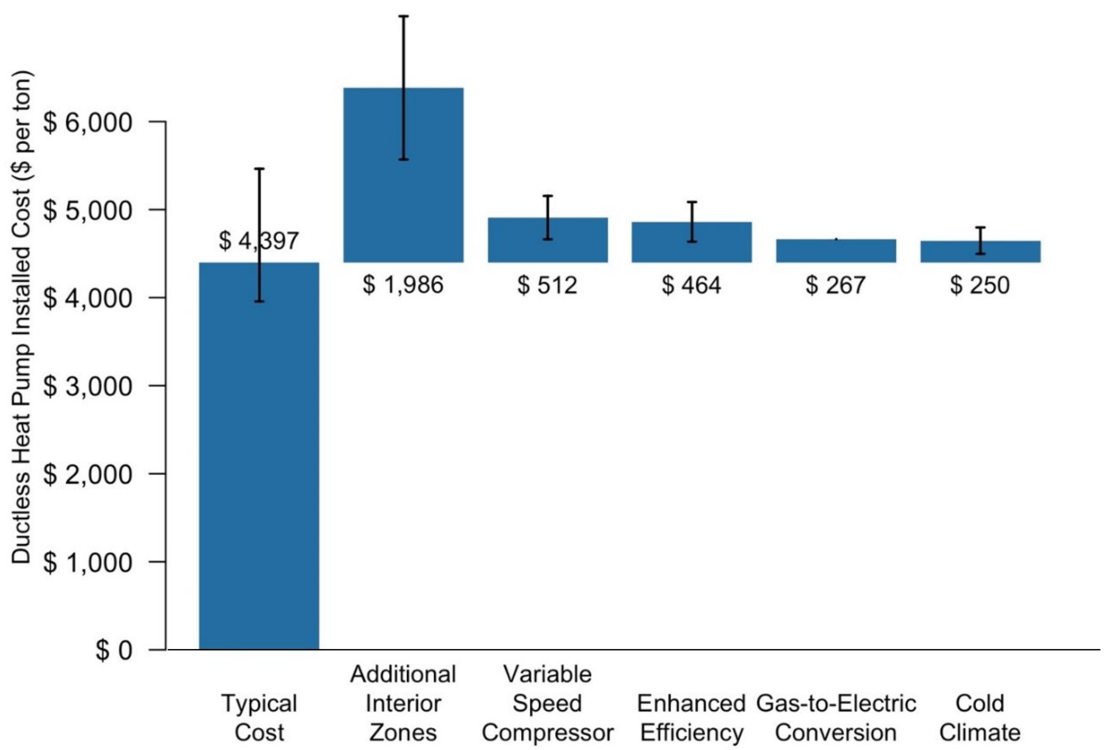


Figure 55. Estimated cost increases per ton for ductless heat pump performance features. Source: (Less et al., 2021)

(Less et al., 2021) also summarized available cost breakdowns for ductless heat pump costs based on labor, materials, markup and other costs. Summaries from (Navigant Consulting, Inc., 2018b)[15] and (Armstrong et al., 2021)[16] are shown in Figure 56. These two cost breakdowns are notable for having very different labor estimates ($1,319 vs. $300), and for inclusion of a 40% business margin in the Armstrong et al. estimate. Including this 40% margin in the equipment cost of $1,666 ($2,332) brings the Armstrong estimate very close to Navigant's ($2,418). Similarly, if Electrical work is counted as Labor, once again, the Armstrong estimate becomes quite similar to Navigant's ($1,100 vs. $1,319). Both versions are clear that the equipment is the largest portion of installed cost for ductless heat pumps, followed by either business margins or labor, depending on how accounting is done. Permits, supplies and other costs are fairly marginal.

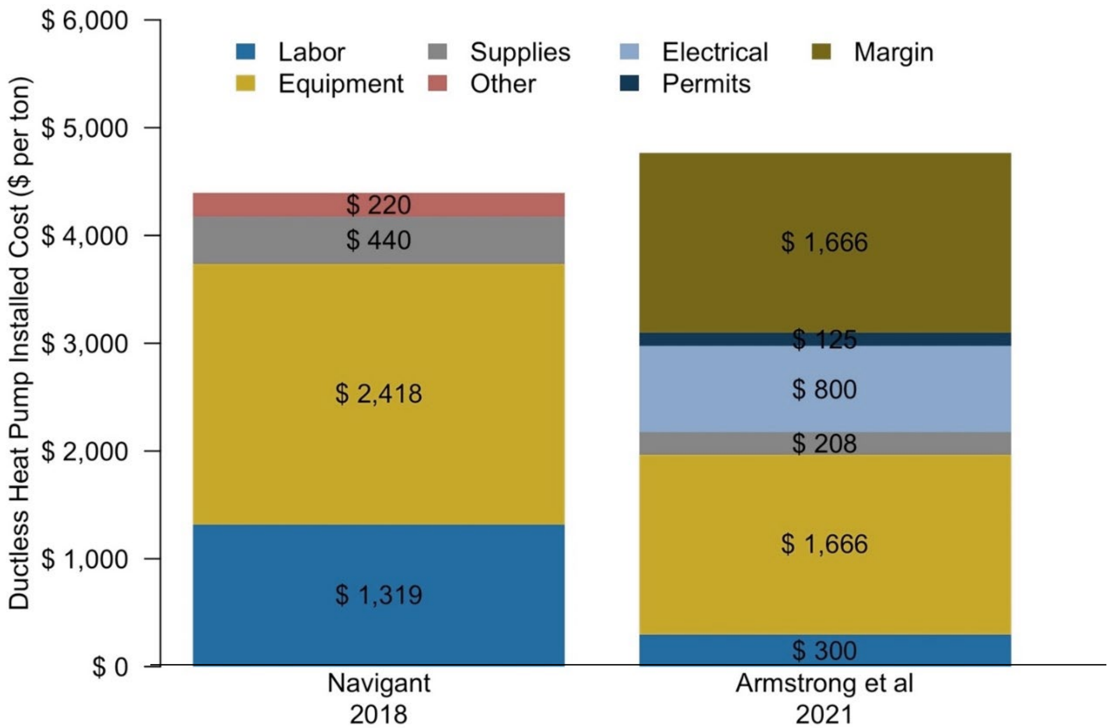


Figure 56. Cost breakdowns for ductless heat pumps in the research literature. Source: (Less et al., 2021).

In the database, ductless heat pump costs most clearly varied with the system capacity, scaling in near-linear fashion from <1 ton up to 4.5 tons, as shown in Figure 58. The vast majority of systems were in the "0.5-1" ton up to the "4 to 4.5" ton range. Larger systems were so few that their distributions are unreliable for comparison.

---

[15] Navigant used a combination of contractor surveys and web scraping of retail equipment price data to estimate cost breakdowns for a 1-ton, 15 SEER and 8.2 HSPF unit: 30% labor, 55% equipment, 10% supplies, and 5% other costs. These fractions are applied to the typical installed cost in the database of $4,397 in Figure 54. Contractors reported charging equipment costs to customers that were on average $875 greater than the lowest retail values available online. This mark-up was consistent irrespective of system size/type.

[16] (Armstrong et al., 2021) provided a ductless heat pump cost breakdown with similar but distinct categories, including electrical work, business margins and permit costs. They report equipment costs to the contractor of $800 to $1,400, but typically $1,200 per ton. This is marked up to $1,110 to $2,100 to the customer. Electrical upgrades are reported from $600-1,000. Labor, materials and other costs are added on top of this.

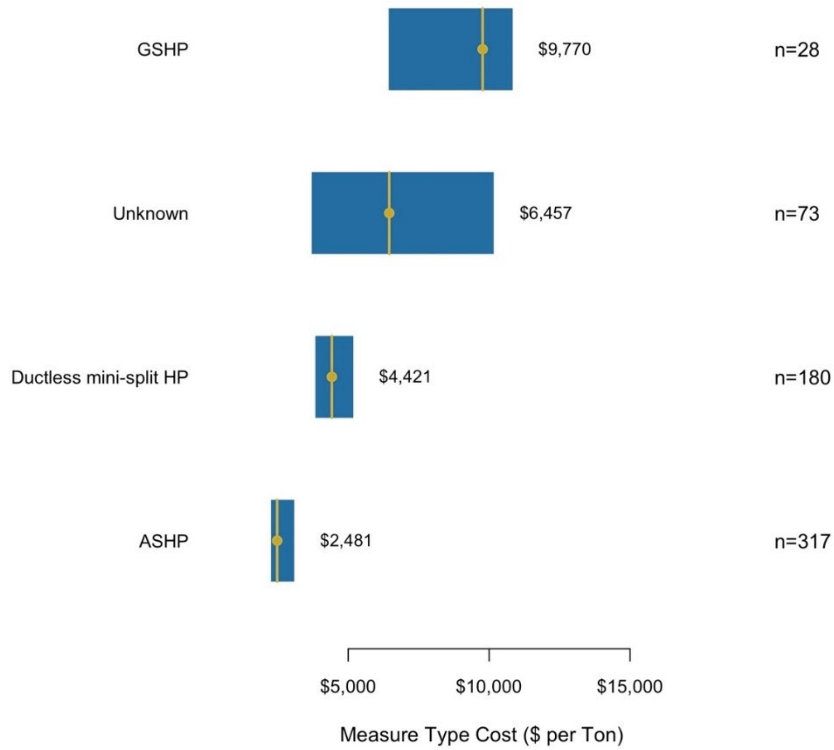


Figure 57. Heat pump installation costs per ton.

Figure 58. Ductless heat pump installation costs by system capacity (tons).

The system capacity normalized costs did not vary consistently with either the heating or cooling efficiency ratings. In fact, both efficiencies showed inverse relationships with cost in the most frequently reported efficiency categories, from 9-14 HSPF and from 17-22 SEER. These results suggest that more efficient equipment had lower installed costs per ton. This does not reflect actual pricing, and we expect that these effects in the data set reflect the specifics of certain models/manufacturers of ductless heat pumps, along with when, where and by whom ductless these systems were installed. Based on the literature review by (Less et al., 2021), enhanced ductless heat pump efficiency (e.g., going from SEER 16 to 18) has a per ton cost range of $239 - $689. Across a sample of installations, unit efficiency does not appear to be a strong driver of installed cost.

Cold climate ductless heat pump models showed a median price premium of $192 per ton over standard units, though it is important to know that many systems in the "Standard" category may have been cold climate models that were not adequately labeled in our data sources. The price premium for cold climate models based on the literature review by (Less et al., 2021) was $100-$400 per ton.

10.1.2 Furnaces

A total of 436 furnaces were installed with 18 identified as two-stage. Others may be two-stage but were not identified as such in project documentation. The median cost was $5,025 (about $2.70/ft^2) with an interquartile range from about $4,000 to $6,000. Gas furnace costs were much less variable by heating capacity, such that higher output systems were not substantially more expensive in this dataset.

10.1.3 Cooling – Central Air Conditioner

A total of 71 central air conditioners were installed with a median cost of $5,930 ($2,000/ton and $2.93/ft^2) with an interquartile range from about $4,000 to $9,000.

10.1.4 Ducts

Over 200 duct system replacements and over 300 duct sealing measures were recorded in the database. Most of these had unspecified material types, while a small subset was clearly insulated flex duct. Across the recorded duct types, system replacement median costs were consistently between $3,645 and $3,953 (about $2.15/ft^2), with an interquartile range of about $2,000 to $5,000. Duct air sealing costs were typically much lower (median costs of $789). Duct sealing costs were remarkably stable across levels of leakage reduction, with median costs unwavering between 10-80% leakage reduction.

10.1.5 Ventilation

Mechanical ventilation is a critical element of energy retrofits that reduce air leakage. The (ASHRAE 62.2, 2019) ventilation standard has built-in approaches for determining when a mechanical system is necessary, based on background envelope leakage rates, climate and building characteristics. Nevertheless, installation of mechanical ventilation was infrequent in this database, with only 65 installations recorded in over 1,700 projects. These were roughly split between low-cost exhaust fan units and higher-cost units with heat recovery (both ERV and HRV). Overall, installation of mechanical ventilation added $733 to a project. When disaggregated by ventilation fan type, the costs varied substantially. Exhaust fan median costs were $748, while heat recovery unit median costs were $2,835.

10.2 Air Sealing

The air sealing measure costs normalized by dwelling floor area are shown in Figure 59. More detail is provided on air sealing costs for envelope and duct sealing in Appendix Sections G.3 Seal, G.7.4 Ducts and G15.1 Envelope Air Sealing.

Envelope air sealing costs were proportional to leakage reductions, but only marginally, from around $600 for <30% reductions to around $900 for reductions >40%. The most important factors in determining air sealing cost were the Program the project participated in, followed by the leakage reduction, the climate zone, and the post-retrofit CFM_{50} value. It is important to note that the costs of air sealing reported in the database are for direct air seal actions only, and do not include the costs of other measures that might also contribute to leakage reductions (e.g., window replacement, dense pack insulation, etc.). As a result, these costs might underestimate the expense of air leakage reductions when used in isolation from other upgrade measures.

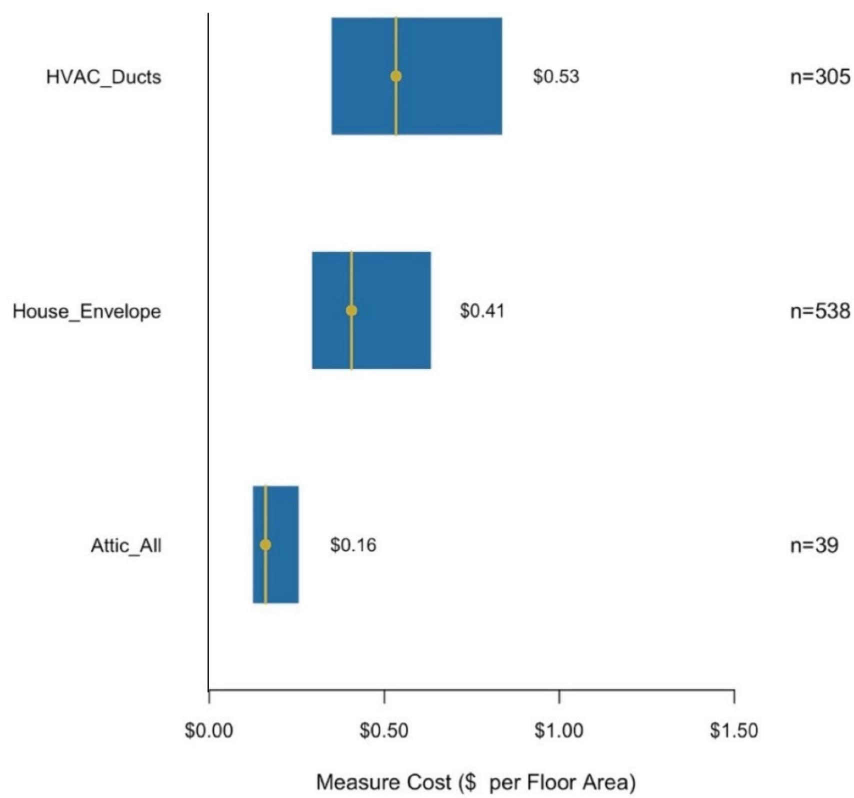


Figure 59. Sealing cost distributions per dwelling floor area.

Duct sealing costs were remarkably stable across levels of leakage reduction, with median costs nearly unwavering between 10-80% leakage reduction (see Appendix Figure G 32 and Figure G 33 for total costs and floor area normalized costs by leakage reduction). Some very slight increases in sealing costs are evident when going from 30 to 70% duct leakage reductions, which increased costs by roughly $0.10 per ft². This suggests that most duct sealing work is bid on a fixed-price approach, and either some contractors are much more effective at reducing duct leaks for a given cost, or some houses simply have greater potential for reduction.

10.3 Insulation

Insulation measure costs per ft² of treated surface area are plotted in Figure 60 organized by envelope component. These same data are shown further normalized by assembly R-value in Figure 61. The R-value normalization allows one to estimate typical costs based on the insulation level achieved. The assumption is linear, which does not account for relatively higher costs at lower R-value, due to fixed business and project costs that do not scale with R-value (e.g., travel, preparation, clean up). Foundation insulation measures were amongst the most expensive, including band joist, framed floor and basement wall components. Many of the higher costs reflected in this figure are the result of the use of more expensive insulation materials (e.g., spray foam insulation). The lowest insulation costs were in attic framed floor assemblies, knee walls and framed walls. Insulation costs in the Sections with the greatest number of reported measures are discussed below in Section 10.3.1 through Section 10.3.3.

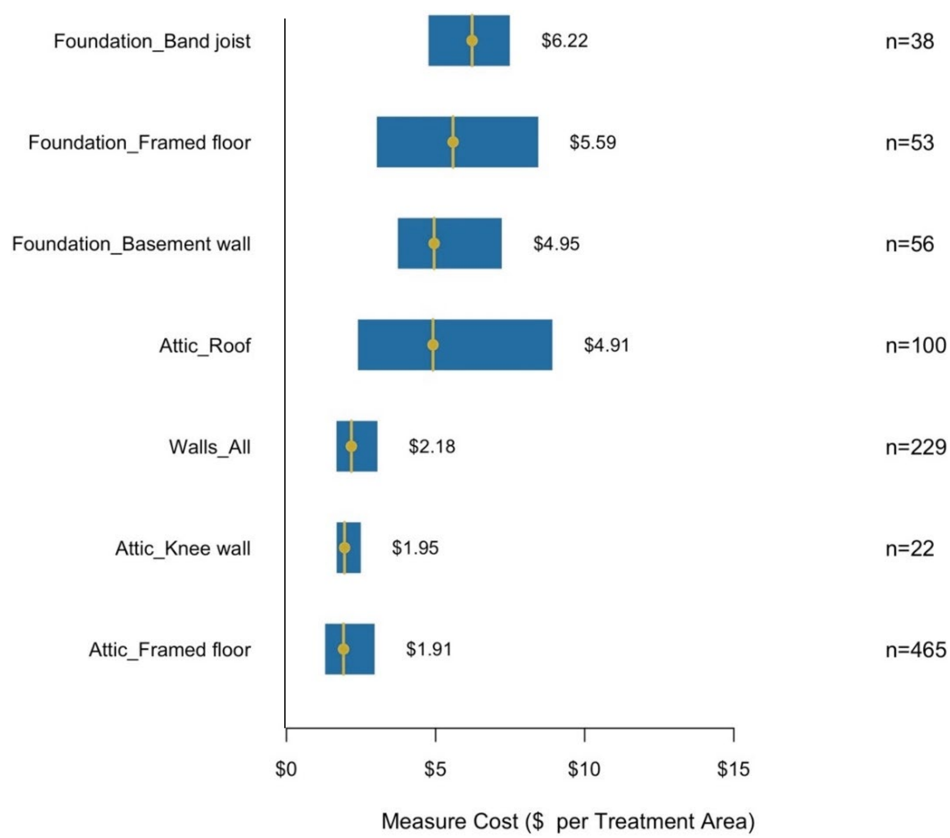


Figure 60. Insulation cost distributions per treatment area, by building component.

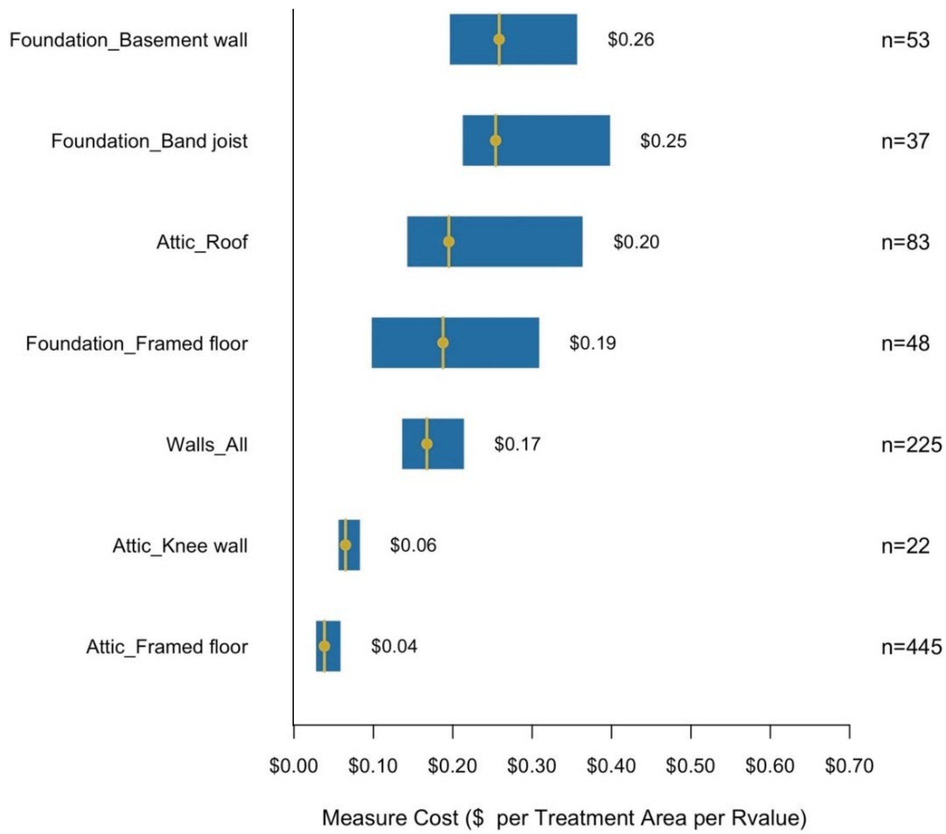


Figure 61. Insulation cost distributions by R-value per treatment area, by building component.

10.3.1 Attic

The attic section was the third most frequently recorded in the database (after HVAC and House sections), with 1,061 recorded measures with costs, totaling $2.71 million (2019 $USD) for insulating attics. By far the most frequently reported attic measure was insulation of the framed floor surface, followed by attic rebates and roof insulation.

The materials used, and the surface being insulated had substantial impacts on the attic measure costs. Attic knee-wall insulation was exclusively with fiberglass batts in the database with a median installed cost of $1.95/ft^2. Blown cellulose insulation was a low-cost means to insulate the attic framed floor, with median normalized costs of $1.46 to $2.88 per ft^2 of treated surface area (depending on insulation material) at a median R-value of 44 ($0.05 per ft^2 of surface area per R-value). Insulating the roof surface was generally much more expensive, ranging from a median cost of $6.40 per ft^2 for cellulose insulation, up to a median of $8.32 per ft^2 of treatment area or closed cell spray foam insulation. A low-cost option for roof insulation was dense packing rafter cavities in finished attics, which had a median cost of $2.01 per ft^2 of treated area. Yet, when normalized by installed R-value, the cost per ft^2 of treatment area was similar across all sloped roof insulation types (median values from $0.18 to $0.21 per ft^2 per R-value). In this dataset, compared with insulation placed on the attic framed floor (e.g., blown cellulose), sloped roof insulation was typically lower R-value (R-19 vs. R-44) and more than double the cost ($4.91 vs. $1.91 per ft^2). In addition, sloped roof insulation requires greater surface area than framed floor approaches, which can increase total cost and surface area for heat loss/gain. When other design goals allow (e.g., the attic is not going to be conditioned space), framed floor blown insulation is the most cost-effective approach to attic retrofit.

Roof insulation upgrades were summarized from the research literature by (Less et al., 2021). The range of costs reported in the literature for attic and roof insulation upgrades are shown in Figure 62. Once again, the error bars show the range of reported values, not the standard deviation or other statistical measures. The costs from the literature were higher than those reported in the database projects, across all assembly and insulation types. The values in the database are consistent with the lower bounds of the values reported in the literature.

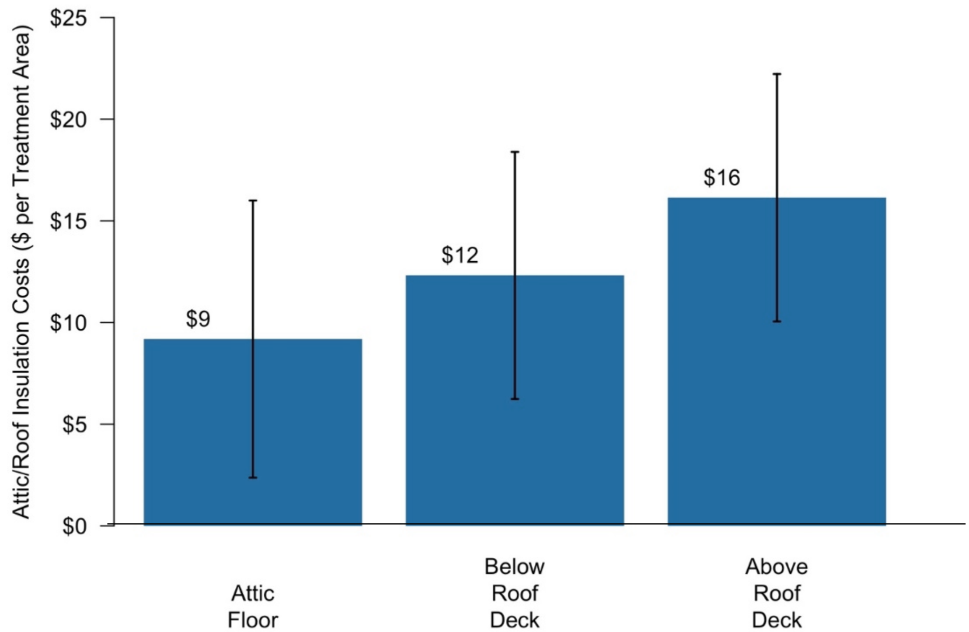


Figure 62. Attic and roof insulation costs from the literature, (Less et al., 2021).

10.3.2 Walls

The wall section was the fifth most frequently recorded in the database, with 289 costed measures, totaling $1.1 million (2019 $USD). Overall, very few projects included exterior wall insulation that would achieve R-values exceeding the typical R-11 to R-15 values in framed wall cavities. The median cost to blow insulation into cavities was about $1.70/ft^2$ from the inside, rising to about $2.00 - $2.50/ft^2$ when installed from the outside. These reported costs varied by almost a factor of two between quartiles. The most important variables in determining wall costs were the type of insulation, treatment area (ft^2), followed by program participation, location (cavity vs. exterior) and R-value.

Of the 265 projects that reported wall insulation measures, only 15 included insulation on the exterior. Of these 15, very few of them recorded efforts to wrap the entire exterior of the dwelling in insulation. Rather, smaller wall sections were addressed on the order of hundreds of square feet. Exterior insulation was much more expensive (by roughly 4x), with a median cost of $9.36/ft2 compared with $2.24/ ft^2 for cavity fill projects. (Less et al., 2021) reported on upgrade costs of adding exterior wall insulation to energy retrofit projects. The typical values and reported ranges of exterior wall insulation costs with and without exterior finish/cladding are shown in Figure 63. This exterior insulation cost is at the low end reported in the literature review by (Less et al., 2021). The lowest achievable cost for adding exterior wall insulation in the literature was in the range of \$5 - \$7 per ft^2, as many of these prices were derived from projects where concerted R&D efforts were being made to identify the lowest cost approaches to insulating the exterior of walls. The range of database values (roughly \$5 - \$13 per ft^2) is consistent with the literature values. These marginal costs might be justifiable in some cases where the exterior cladding is already being removed and replaced. If not aligned with re-siding, total upgrade costs for exterior insulation and cladding replacement are typically >\$15 per ft^2.

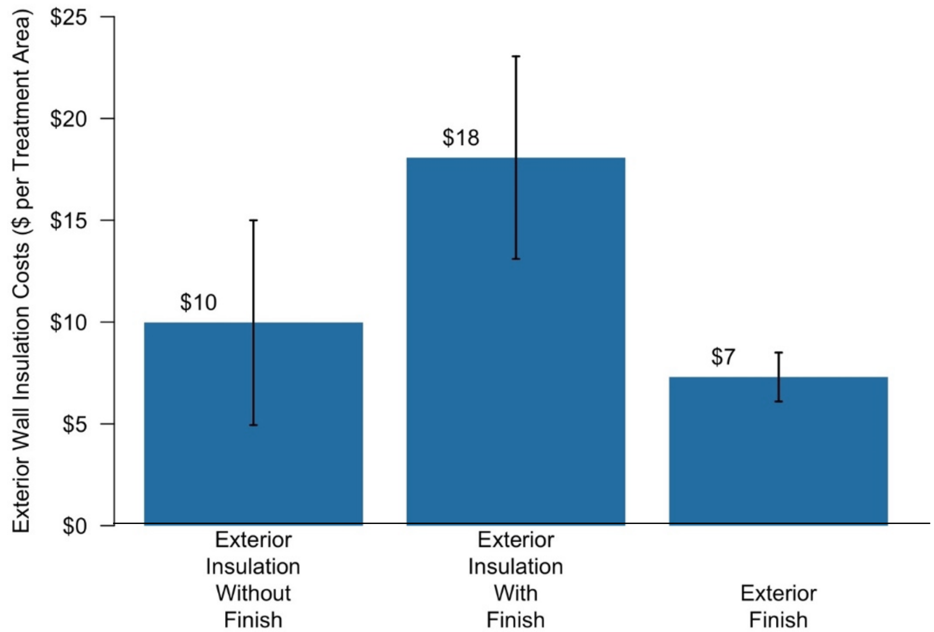


Figure 63. Exterior wall insulation cost ranges from the literature, from (Less et al., 2021).

10.3.3 Foundation

The Foundation section was the 6th most common for recorded measures (exactly tied with Plumbing), with a total of 274 measures, totaling \$650,000 of capital investment. The vast majority of foundation measures were insulation. Typical framed floor and basement wall insulation costs were very similar, with median project costs of \$1,500 - 1,600 (\$5.59 vs. \$4.95 per ft^2 of treated surface area). These framed floor costs are quite high relative to the normalized costs for attic framed floor and wall insulation measures. There are two primary drivers of the high normalized costs of framed floor insulation. First, as discussed below, this is partly due to frequent use of closed cell spray foam insulation for foundation framed floor, which drives up the median costs. Second, are the high costs of suspending lower-cost fibrous insulation in a framed floor assembly, as opposed to the ease of loose fill insulation on an attic floor.

Foundation insulation costs were also determined in the literature review by (Less et al., 2021), and the high-level summary is reproduced below.

- Sealed and insulated crawl: \$3.61 - \$5.80 per ft^2; total: \$5,500
- Basement wall exterior: \$3,792 - \$7,593 (up to \$20,300)
- Basement wall and slab interior: \$21,500 - \$28,406 (wall-only: \$7,000)
- Slab-on-grade perimeter: \$16.51 per linear foot

Basement wall insulation projects recorded in the upgrades database were much lower cost (median of $1,544) than the example project costs from the research literature. The treatment area normalized costs in the database were $4.95 per ft^2 for basement wall insulation, which based on the reported total measure costs, suggests that typical basement insulation only addressed roughly 300 ft^2 of area (1,544/4.95). It is possible that only the upper portions of basement walls that are above grade were being insulated in projects in the database, which are the areas with the greatest exposure to exterior conditions and highest rates of heat loss.

10.4 Windows and Doors

The windows and doors sections were the least frequently addressed in the projects in this database. Only 76 window and 42 door costed measures were recorded. Window installations typically cost from $3,000 to $12,000 (median $6,500 to $7,500), with a typical cost per window unit of $674. Most projects did not address the exterior doors. Median cost for the 31 door replacements was $1,480, while the 10 cases of weather-stripping install were $99.

10.5 Water Heating

Water heater installation costs are summarized by type in Figure 64. Electric heat pump water heaters were the most frequently installed in the dataset, followed by tankless gas and storage electric units. The tankless gas units were by far the most expensive, with median costs of $4,004. The heat pump units were over a thousand dollars lower in cost, at $2,824. Though electric heat pump water heater costs varied substantially by tank size, with 50-gallon and 80-gallon median installed costs of $2,242 and $3,828, respectively. While not explicitly recorded in the database, we suspect that tankless gas costs were so high due to requirements to replumb the typical ½" gas lines up to ¾" for high-output tankless gas heaters. The existing plumbing type was typically unknown, so we do not know how many of the heat pump units were replacing gas vs. resistance electric tanks. Existing electric systems would not require costly electrical upgrades, while replacement of gas equipment typically incurs additional costs. These differences may explain the roughly $1,500 interquartile range in heat pump water heater costs. Having said that, the storage gas units have an interquartile range of about $1,000 around the $1,972 median installation cost. So, it is possible that many other factors affect the costs of installing replacement water heaters.

(Less et al., 2021) summarized heat pump water heater installation costs reported elsewhere in the research literature (see Figure 65). (Navigant Consulting, Inc., 2018a) provided two cost estimates. First, based on web scraping of prices and creation of a cost curve based on size and efficiency, and second, based on contractor interviews. The SMUD estimates are based on several thousand units installed as part of a SMUD electrification program in existing homes. Navigant estimated the cost breakdown for heat pump water heaters: labor (23-28%), equipment (55-66%), supplies (7-12%) and other costs (4-6%). These are applied to each of the three heat pump water heater cost estimates in Figure 65. The 50-gallon heat pump water heater installations in the SMUD program are much more expensive than typically reported in our database ($3,800 vs. $2,242), while the estimates from (Navigant Consulting, Inc., 2018a) are similar to costs reported for both tank sizes in the database. As with ductless heat pumps, equipment costs dominate the installed costs of heat pump water heaters.

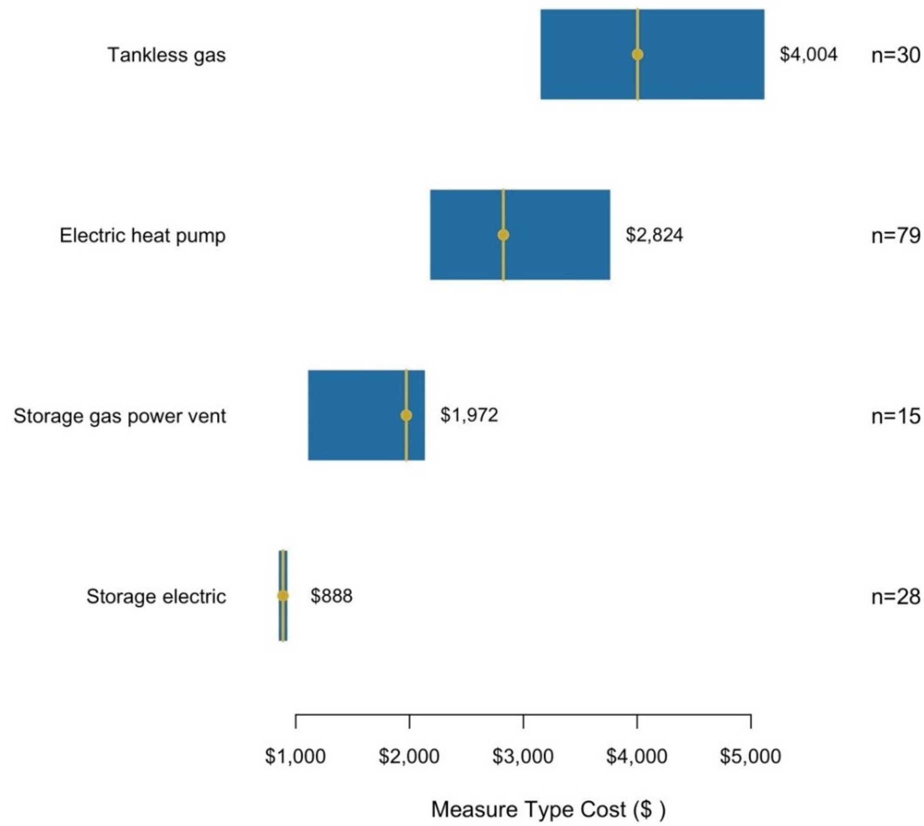


Figure 64. Water heater installation costs.

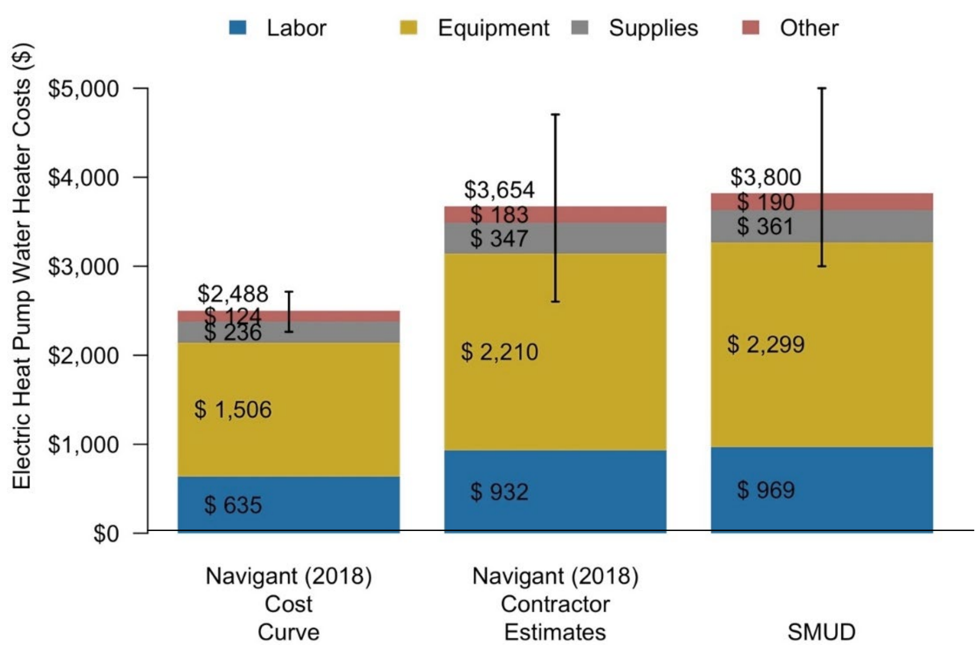


Figure 65. Electric heat pump water heater installation costs from the literature, (Less et al., 2021)

10.6 Electrical (Lighting and PV)

The electrical section is the fourth most frequently recorded in the database, with 360 costed measures and a total expenditure of $2.4 million USD. The electrical measures are dominated by PV installation (n=68) and lighting upgrades (n=267).

Electrical panel service upgrades are common in existing homes with lower total amperage panels (e.g., those 100 Amps or less). The upgrading of electrical service to 200 Amps is of growing importance, as end-uses in homes are converted from gas to electricity, and as other loads require a patch to interface with the grid, including electric car charging and household battery charging technologies. However, with two exceptions, the database did not have records specifically related to service upgrades. Very few electrical upgrades were explicitly recorded in the database, though we expect that many HVAC and hot water measures included electrical expenditures as part of the work scope. Only five "wiring" measures were recorded, ranging from $200 to $800 (median of $679). It is likely that any electric system upgrades were included in other measure costs. For example, heat pump water heater installations may include the costs to run a new circuit for the heat pump.

For PV systems the median installed capacity was 6.7 kW, varying from roughly 2 up to >15 kW in some instances. The cost of PV installation normalized by capacity declined in the dataset based on the year of installation. The median costs dropped from $6,388 per kW in 2011 to $2,795 per kW in years 2019 and 2020 combined. These reductions are consistent with other efforts to benchmark the cost of solar PV over-time. For example, the NREL residential solar cost benchmark shows costs for a 22-panel residential system of $7,530 and $6,620 per kW in years 2010 and 2011, with prices dropping down to a range of $2,710 to $2,780 per kW in years 2018-2020 (NREL, 2020). The installed capacity of the PV system was also important in determining the system cost. As system size increases, the trend is towards lower normalized costs, such that a small 3.5 kW system is roughly $3,800 per kW, while a larger 12 kW system is roughly $2,750 per kW.

As LED bulbs have become commonplace and dramatically lower cost over the past decade, they have replaced compact fluorescent bulbs as the retrofit lamp of choice (194 projects vs. 44 projects using CFL). The LEDs are also lower cost on a per unit basis, at $6.88 vs. $7.81 per fixture. Of those projects that recorded lighting upgrade measures, typically 17 bulbs were replaced at a median cost of $6.88 each. For all lighting measures (including those lacking bulb/fixture counts), the median cost was $143.39. Some projects recorded very large lighting upgrade costs, on the order of $10,000 to $50,000. We do not have specific details on these projects, but we hypothesize that these costs included re-wiring and whole fixture replacement (as opposed to swapping bulbs).

10.7 Appliances

Appliance upgrades were uncommon in the projects contributed to the database, with only 100 costed measures across all appliance types. Refrigerators were replaced most frequently (median $1,092; n=50), followed by dish washers (median $643; n=19), clothes washers (median $1,791; n=13) and clothes driers (median $1,966; n=11). One induction range upgrade was recorded in the database, at a cost of $2,317. We note that there is a wide range of appliance costs with entry-level induction appliances are available for $599-699 for cook tops and $1,099 for ranges.

10.8 Testing and Commissioning

Both testing and commissioning costs were infrequently reported and were inexpensive. Testing measures recorded in the database included only combustion safety testing (median of $222) and test-out procedures (median of $316). Commissioning measures were recorded solely for blower door testing the house. These were only recorded by one program, which had consistent and low testing costs of $78 on average.

10.9 Demo and Disposal

Demo and disposal actions were very infrequently reported in the database, but when reported, they could be substantial costs. These costs were dominated by insulation removal from attic framed floors, and removal of asbestos contaminated products. The cost of insulation removal ($1,608) is roughly equivalent to the cost of new attic framed floor insulation ($1,827), which means the decision to remove insulation could effectively double the project costs. This should only be done when contamination levels are unacceptable, or when other activities, such as air sealing or wiring addition/replacement is impossible with existing insulation in place. Asbestos removal costs average $906, and these costs may not be avoidable.

10.10 Reconfiguration (Adding Space to the Home)

The Reconfigure action was intended to be used for wholesale changes to the boundaries of the building envelope or its systems. It was used very infrequently, in part because of few reconfigurations works in the retrofit projects submitted, but also due to likely categorization of measures in other ways. For example, conversion from a vented to a sealed attic space may have just been recorded as an Attic_Insulate_Roof measure. The reconfigure efforts recorded were for foundation conversions from vented to sealed crawlspaces or from unconditioned to conditioned basements. The reconfiguration costs had a median of $2,680 with an interquartile range of about $2,000 to $12,000.

11. Affordability

Given the significant investments required for most homes, it is unlikely that many homeowners will have the cash in hand to able to perform deep upgrades and electrification in their homes. While we recognize that financing will always increase project costs due to the costs of servicing a loan, it is the only practical way to get to scale with energy upgrades and decarbonization. As discussed in the metrics section, there are several ways to assess affordability including several new metrics associated with decarbonization and electrification. Developing innovative analyses to support new metrics is beyond the scope of this study, therefore, we will concentrate on traditional metrics as those are currently most prevalent and are still considered relevant by many industry practitioners.

11.1 Financing and Cash Flow

Overall, project financing was uncommon in the upgrade project database, and most households paid for project work out of pocket or through other means. Financing is also uncommon more broadly in general residential remodeling (Guerrero, 2003) and in other energy upgrade databases (Palmer et al., 2013). In all, we are confident that financing was used for 467 projects in the database (27%), though that number may very well be higher, because most projects did not record financing information. The Home MVP program in Massachusetts offered 0% interest, 7-year financing for program participants. Of the 357 projects contributed from the Home MVP program, 135 used the available financing (38%). Projects that participated in Pay-as-you-save programs (e.g., EEtility) were also implicitly financed. These amount to a total of 332 projects. For comparison, of the 75,110 projects whose information was recorded during the DOE Better Buildings Neighborhood Program (BBNP), only 12,360 (16%) were financed using loans[17]. In a review of the literature, Less et al. (2021) concluded that energy upgrade projects often do not use financing, even when it is available. There is some evidence reviewed by Less et al. suggesting that use of financing is more common in projects that had greater energy savings. For example, in an analysis of Energy Upgrade California projects, those projects with the greatest savings ('Savers') used financing roughly half the time (49%), while projects with lower savings used financing much less frequently (30%). Similar results were observed for the BBNP program (Heaney & Polly, 2015), where financed projects generally had higher savings and nearly double the investment in the upgrades. However, as this study has shown, *greater investments are needed to achieve our decarbonization goals and this may make financing more attractive, in addition, any substantial participation by middle and low-income households will require financing, either at the program- or project-level, because most households lack the funds to pay for upgrades outright.*

Our financing and cash flow analysis includes an assessment of monthly cashflow (i.e., net-monthly homeownership costs) under a variety of financing scenarios representative of loan products available for home renovation/upgrades (i.e., 10-, 20- and 30-year; 0, 3 and 8% interest). We also include an analysis of PAYS-type repayment terms, where upfront program fees of 3% are included in the principal of a 12-year repayment loan with 0% interest. Note: these financing analyses were for the gross project costs and do not include the reduced costs associated with rebates, and therefore represent a worst-case in terms of household cashflow. See APPENDIX F.3 Financing and Cash Flow for additional data plots addressing financing and cashflow.

[17] BBNP data is publicly available here: https://openei.org/doe-opendata/dataset/better-buildings-neighborhood-program-single-family-home-upgrade-project-dataset

In Figure 66, the monthly cashflow (i.e., balance of monthly loan cost vs. monthly energy cost savings) is assessed for all projects in the database that included both energy cost savings and total project costs (n=1,212). In this plot, positive values show increased net-monthly ownership costs (savings are less than loan costs; “bad”), while negative values indicate reduced net-monthly ownership costs (net-cost savings; “good”). Under most financing scenarios examined, the median net-monthly ownership costs increase by between \$6 to \$59 per month. In other words, under these financing assumptions, household costs increased rather than decreased post-upgrade. For a program covering a portfolio of homes, these results are promising, because central values are near-zero. But for individual homes on the high-end of monthly costs, this may present a significant problem/barrier to energy upgrade adoption. Furthermore, these results indicate that a combination of rebates together with financing is necessary to reduce the risks to homeowners of increased monthly costs.

Unsurprisingly, longer loan terms and lower interest rates for the mortgage-based loans reduce monthly cashflows, because these factors reduce the monthly loan payments. For the 30-year loan at 3% interest, the result was net-monthly cost savings in over 50% of projects. PACE-type terms (see the 20-year, 8% values) had middle-of-the-road net-monthly costs (+\$26 per month), because high interest rates were offset by relatively long financing periods. While this analysis indicates that typically energy upgrades were very close to cost-neutral, any program (or potential home owner) needs to be aware of the potential for substantial increases in monthly ownership costs (i.e., >\$50 per month in roughly 10% of projects). Programs should pay special attention to projects that potentially fall into this category, namely those with higher project costs and the greatest savings goals. These projects are most cost-effectively supported by long loan terms with low interest rates.

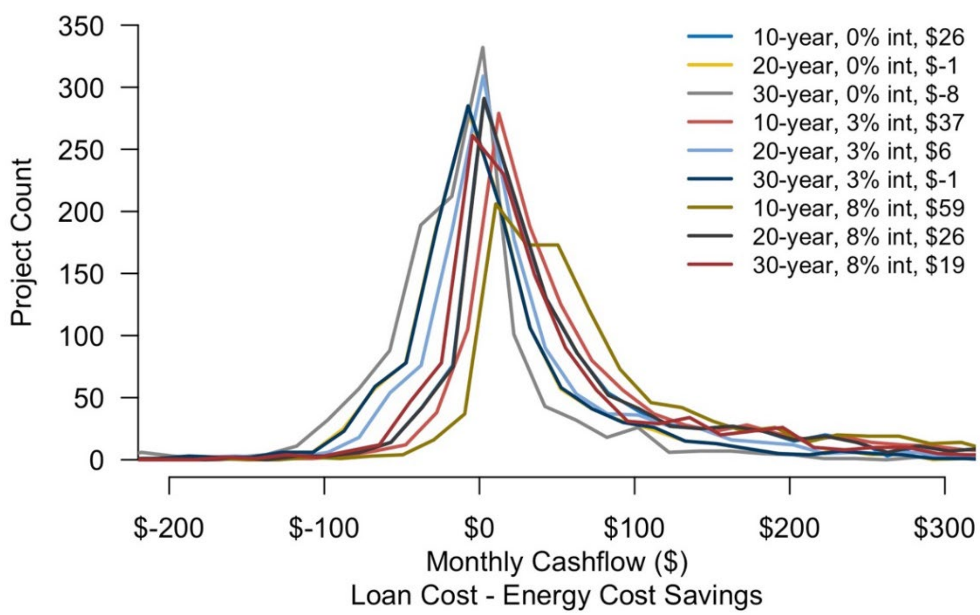


Figure 66. Net-monthly cashflow under nine financing scenarios, including three interest rates (0, 3 and 8%) and three loan terms (10-, 20- and 30-year). Median monthly cashflows are shown in legend. Extreme values are removed from plot window. Negative values indicate net-monthly cost savings post-upgrade (“good”), and positive values indicate net-monthly cost increases post-upgrade (“bad”).

As noted above, financing has costs that can be substantial over the long term. An illustrative example cost-stack is provided in Figure 67 for a hypothetical project that costs \$30,000 (loan principal). The additional cost of the loan is substantial for all terms explored. In this example case, amounting to between 16% and 164% of the principal project cost, and roughly $5,000 to $50,000. This further reinforces the potential impact of rebates and cost reductions. For every dollar rebated there is also an additional saving in the loan servicing cost.

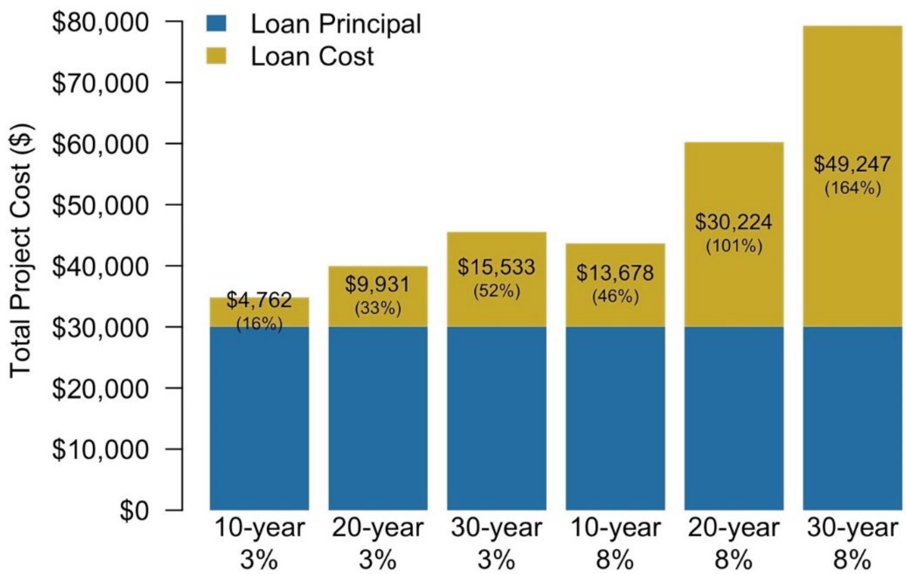


Figure 67. Loan costs illustrated for example project of $30,000.

We repeated the monthly cashflow calculations shown above including a flat 25% rebate across the gross costs reported for each project. The median monthly cashflow is shown for all financing terms, with and without the 25% rebate in Figure 68 (yellow and blue bars, respectively). The relative impacts of a 25% rebate on monthly household cashflow depends strongly on the financing terms. More advantageous financing terms show little benefit to a 25% rebate (i.e., -$1 vs. -$6 at 30-year, 3% financing), while the worst financing terms benefit substantially from a rebate (i.e., $59 vs. $32 at 10-year, 8% financing). Overall, if we compare the impacts of financing terms against the impacts of a rebate, it appears that securing advantageous financing is more likely to benefit household cashflow. For example, shifting from the 10-year, 8% to the 30-year, 3% loan terms reduce monthly cashflow by $60 (from $59 to -$1). This would represent a $60 per month benefit to homeowners. In contrast, the 25% rebate at most reduces monthly cashflow by $27 (from $59 to $32). This analysis suggests that an alternative to rebates is through federal securing of low interest rate (possibly 0%), long-term loans for energy upgrade projects.

The median monthly cash flow values shown above indicate that for most financing scenarios, more than half of projects have increased net-monthly costs after the upgrades. The count of projects that have neutral or reduced monthly costs are shown in Figure 69, for all financing terms, with and without a 25% rebate. The addition of the 25% rebate adds anywhere from roughly 100 to 200 projects to the cost-neutral category. Again, the impacts of the rebate are largest with shorter financing periods and higher interest rates.

We need to keep in mind that very few homeowners will make decisions about energy upgrades or decarbonization based purely on these financial calculations. The companion industry survey (Chan et al., 2021) showed that the industry considers rebates to a be a good motivator for households to undertake home upgrades. There may be others who would be motivated by low-interest loans. The best approach is to include both. Note that this is the approach successfully taken by the auto industry – have both rebates and low-cost loans to secure expenditures of similar amounts for a household.

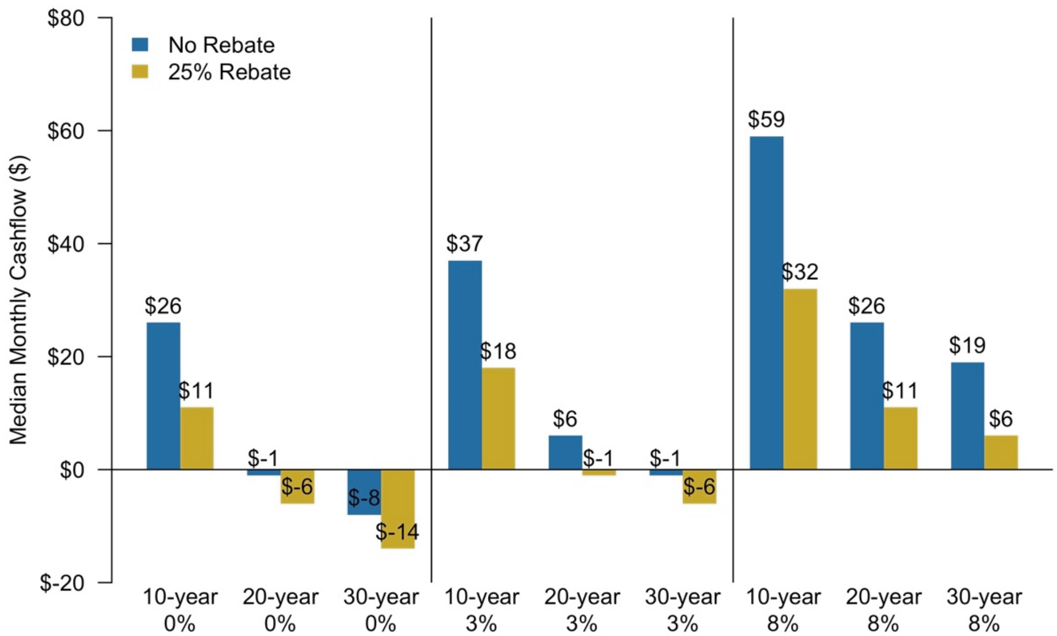


Figure 68. Median monthly cashflow across financing terms and rebates.

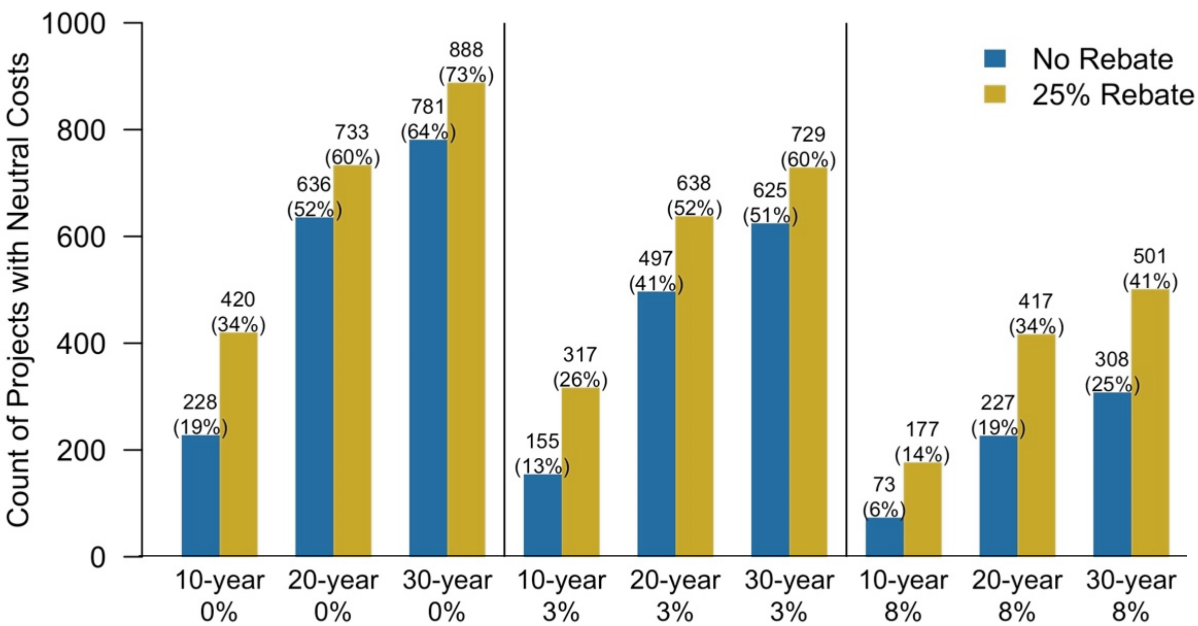


Figure 69. Count of projects that are cost-neutral (or have reduced monthly costs) across financing terms and rebates.

In recent years, some successful programs (e.g., Pay-As-You-Save programs) have avoided traditional economic assessments, such as simple payback, in favor of these cashflow and affordability approaches. Some PAYS providers (e.g., Sealed in New York) finance part of the energy upgrade costs through utility bill savings (the monthly budget), while the homeowners pay the remaining upfront costs out-of-pocket. This allows overall higher levels of investment in the upgrades, while making the investment decision easier for homeowners (e.g., making a $12,000 decision feel like a $2,000 decision).

The PAYS project financing model is unique in that there is no loan provided, instead project costs are covered by a program fee (often 3% of gross costs) and by monthly energy cost savings resulting from the upgrade work. Projects are expressly designed around an intent of being cost-neutral, and overall costs are kept low by using dedicated contractors for the work and by relying on the program for recruitment and customer acquisition. This unique approach was used in 332 projects, and in Figure 70, we compared net-monthly costs for these projects against all others using the same 3% upfront fee, no interest and 12-year payback period assumptions. Median monthly cashflows were -$1 for the PAYS program projects, while they were +$37 per month for all other projects in the data set. PAYS program projects were indeed more cost-effective than other projects when assessed using these terms. PAYS projects met the design intent of being cost neutral on average, but roughly half of the PAYS projects increased net-monthly costs, though almost always by <$25 per month.

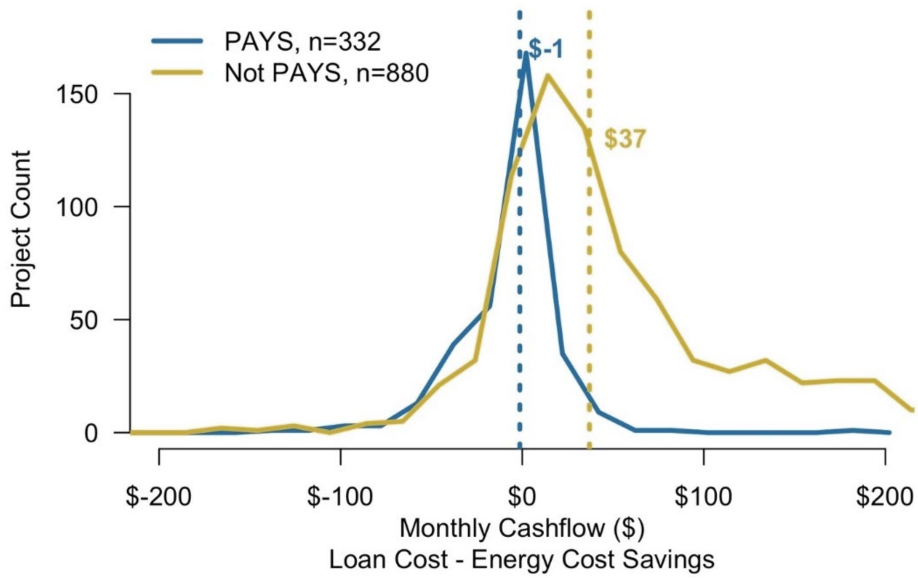


Figure 70. Net-monthly cashflow for Pay-As-You-Save (PAYS) projects compared with all non-PAYS projects. Cashflow computed using 12-year repayment period, 0% interest, with 3% a program fee added to the gross project costs.

11.2 Levelized Cost of Saved Energy

The LCOE distributions for all projects in the database are shown for net-site energy (kWh), energy cost (USD) and carbon emissions (lbs. CO_2e) in Figure 71, assuming a 15-year measure life and 3% discount rate. The median values were $0.11 per kWh, $1.36 per project dollar, and $0.21 per lbs. CO2e saved. The net-site kWh values include all fuel types and do not represent solely electricity. While $0.11 per kWh of site energy saved is competitive with the US average retail price of electricity in 2019 ($0.1054 per kWh), the retail pricing for natural gas is typically much lower nationally ($0.0359 per kWh). If we assumed a 6% discount rate, the LCOE median would have been $0.134 per kWh. For comparison, (Goldman et al., 2020) analyzed a variety of energy retrofit program types, and they reported typical LCOE for whole house retrofit programs of $0.069 per kWh, assuming a 6% discount rate. Whole home programs had the second highest LCOE in Goldman's analysis, while lighting and other single-measure programs had lower LCOE. Low-income energy programs had the highest LCOE of roughly $0.10 per kWh. Overall, the LCOE in the deep retrofit database are aligned with those of low-income programs assessed by Goldman et al.

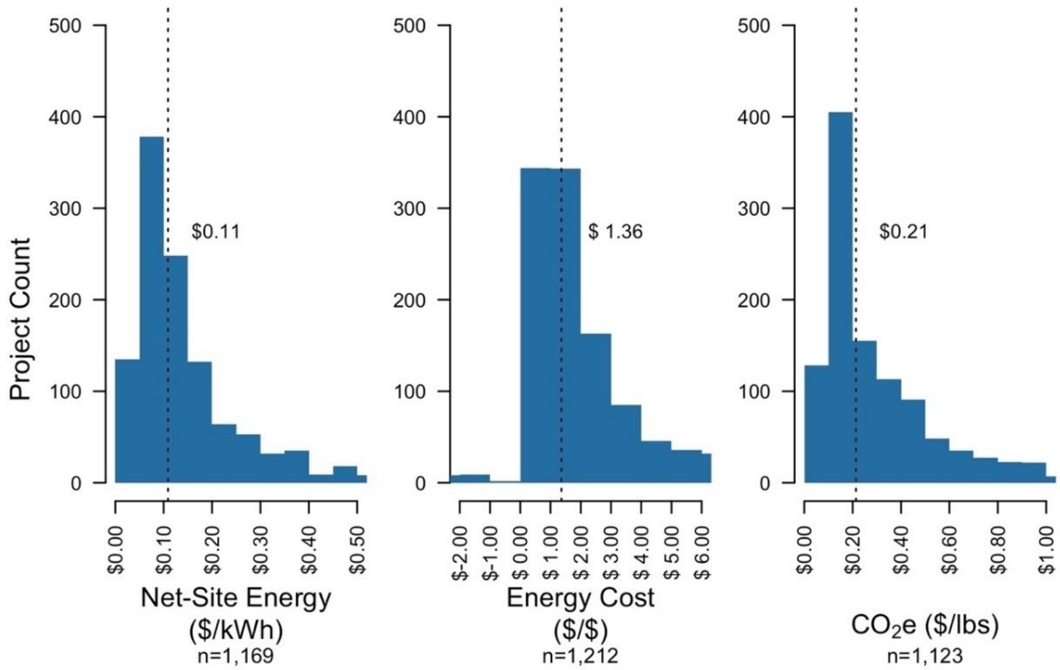


Figure 71. Levelized cost of savings. 15-year measure life and 3% discount rate.

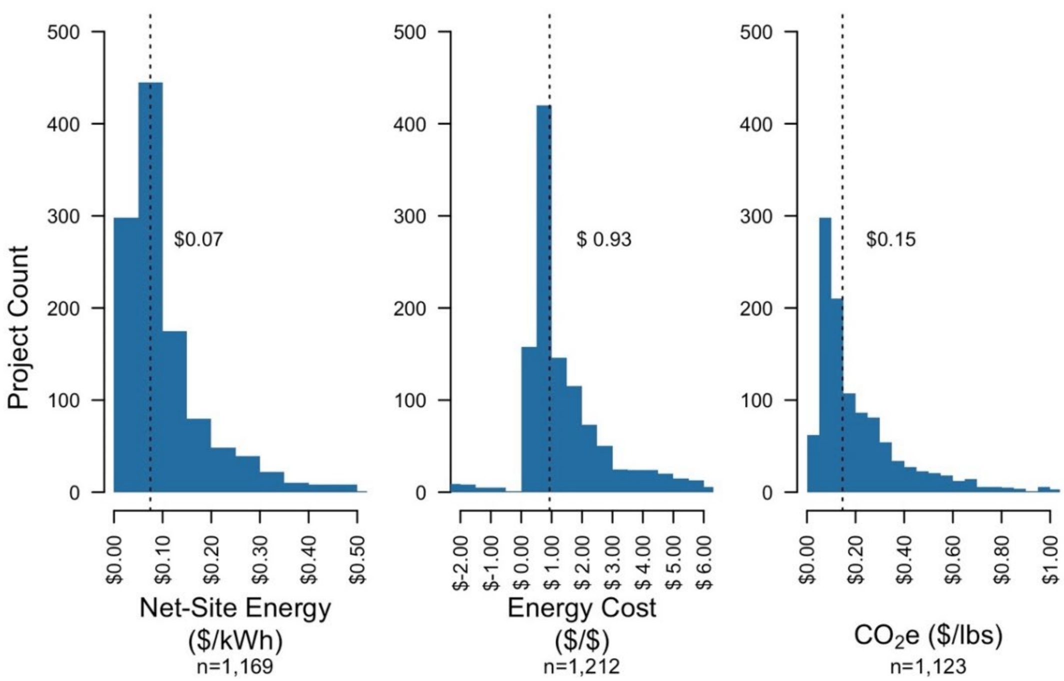


Figure 72. Levelized cost of savings. 25-year measure life and 3% discount rate.

The cost to save energy is relatively high in these energy upgrade projects, because they are targeting higher levels of energy savings than in Goldman et al.'s past assessments. As savings targets are increased, typically the cost to save each additional increment of energy increases. The LCOE generally increased with greater project expenditures, but the relationship was weak ($R^2 = 0.13$), as a wide range of LCOE values were apparent at all levels of project cost. This weak correlation is likely due to other factors affecting the LCOE, such as climate, pre-retrofit condition of the dwelling, equipment/measure types (e.g., cellulose vs. SPF insulation) and project strategies. As discussed later (see Table 9), energy upgrade project types that commonly saved >50% of net-site energy and carbon often had very high LCOE values of $0.18 to $0.39 per kWh saved.

Many energy upgrade measures last for more than 15-years in service (e.g., attic insulation), and many projects included longer-life building envelope measures, or a combination of equipment and building envelope measures. To investigate this, we also examined the LCOE at a 25-year measure life (see Figure 72). As expected, this reduces the LCOE substantially for each metric, with the median net-site cost of saved energy dropping to only $0.07 per kWh, which aligns with the values published by Goldman et al. (although using different assumptions). The median cost per project dollar also drops to below one, suggesting that typical payback periods are 25-years or less at this measure life. Clearly, one way to increase project cost-effectiveness is to implement measures with longer life spans.

The values shown above are for unincentivized gross project costs, but the LCOE are reduced when a 25% rebate is applied to all projects. The median levelized costs with and without a 25% rebate are shown in Figure 73. As in the financing analysis presented above, the existence of a rebate has less impact as measure life increases and discount rates decrease. At shorter measure lives, the 25% rebate reduces median levelized costs per kWh of net-site energy savings from $0.11 to 0.08. At 25-years, the reduction is only from $0.07 to $0.06 per kWh of net-site savings.

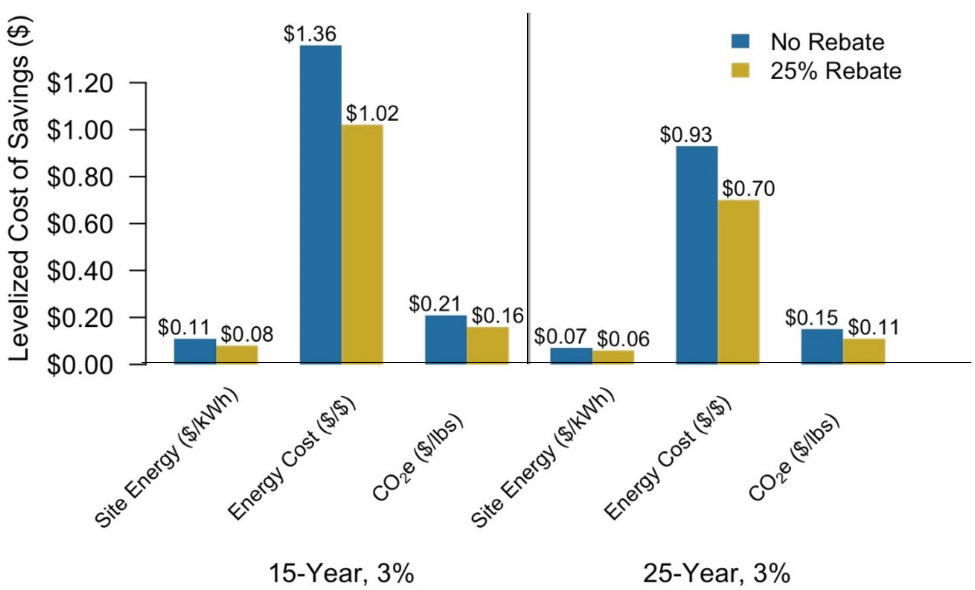


Figure 73. Levelized cost of savings, with and without 25% rebate. 25- and 15-year measure lives and 3% discount rate.

12. Opportunities for Cost Compression

This report determined the amounts of cost compression required for a set of clustered project types based on the present value of the energy cost savings reported for the projects (see Section 4.2). This approach is highly dependent on the analysis assumptions, including energy costs, discount rates, analysis periods, etc. In addition, many consumers might not decide between upgrade technologies or measures based on complex financial calculations with 10-30 year time horizons. Something to be considered in future analyses is compressing electrification to parity with fossil fuel alternatives, such that the cost of a heat pump system is the same as that for a fuel burning appliance.

Opportunities are both necessary and plentiful for cost compression of whole home energy upgrades that meet aggressive energy and carbon reduction goals. Potential cost compression falls under several distinct categories:

- Policy – Rebates, incentives and financing
- Technology
- Business economics (soft-costs, overhead)
- Alternative project designs based on new metrics
- Leveraging no- and low-cost behavioral change and controls

Each of these cost compression paths are briefly explored in sections below. Future research efforts are required to refine, quantify and support implementation of each of these categories of cost compression.

12.1 Policy

Incentives and rebates are widely used to increase the adoption of efficiency technologies, and these types of policy measures are a crucial element of cost compression for the home decarbonization market. Specific policy analyses are beyond the scope of the current study, however, we included an example 25% rebate in our affordability calculations to provide an estimate of the financial impacts of rebates.

12.2 Technology

Technology is a broad category of cost compression that is meant to represent potential improvements and changes to specific retrofit technologies or strategies. For example, lowering the costs of heat pumps, electrification and load reduction technologies. Example waterfall plots showing estimated cost compression pathways for ductless heat pumps and heat pump water heaters are shown for illustrative purposes in Figure 74 and Figure 75. Each technology starts as the median cost recorded in the energy upgrade database, and cost reduction opportunities are plotted as per ton or per unit savings until reaching a target cost. These targets are simply the cumulative impact of all the example cost reductions listed in figure; the target numbers are not based on cost-effectiveness or technical potential. Based on these examples estimated values, ductless heat pumps have a path for reducing typical per ton costs from around $4,400 today to $3,100 (29%), while heat pump water heaters can be reduced from $2,242 to $1,318 (41%). In both of these examples, the greatest savings come from avoidance of new electrical circuits through use of plug-in technologies that use 120V instead of 240V.

In addition to directly changing the material cost of technologies, there are also volume purchasing discounts of 5%, along with 5% soft cost savings that result from being bundled into measure packages are assumed for each technology.

Electrification projects are often saddled with the burden of electrical panel upgrades in situations where the amperage is insufficient to support substantial new loads. The typical cost for a 200 amp electrical panel upgrade is $1,954 (Lane, 2019). Only two panel upgrades were explicitly recorded in the DER database, at an average cost of $1,993. In addition to this, are the actual electrical upgrade costs for each dedicated circuit run to new electrical appliances. Many homes with 50- or 100-amp service cannot support these new loads as required by electrical codes. Emerging technologies are being deployed and tested for electrification upgrades that do not require massive re-wiring or panel upgrades. These include:

- Smart circuit splitters
- Programmable subpanels
- Power efficient appliances

The simplest examples are 240V outlet/circuit splitters that allow for electric vehicle charging using electrical service currently provided for electric clothes driers. The same devices could be used to run an electric water heater alongside another appliance. Controls are implemented that curtail car charging when the auxiliary load is being actively used. Programmable subpanels can achieve some of the same load management outcomes, but without sharing receptacles at the appliance level, and by allowing load sharing across more than two end-uses.

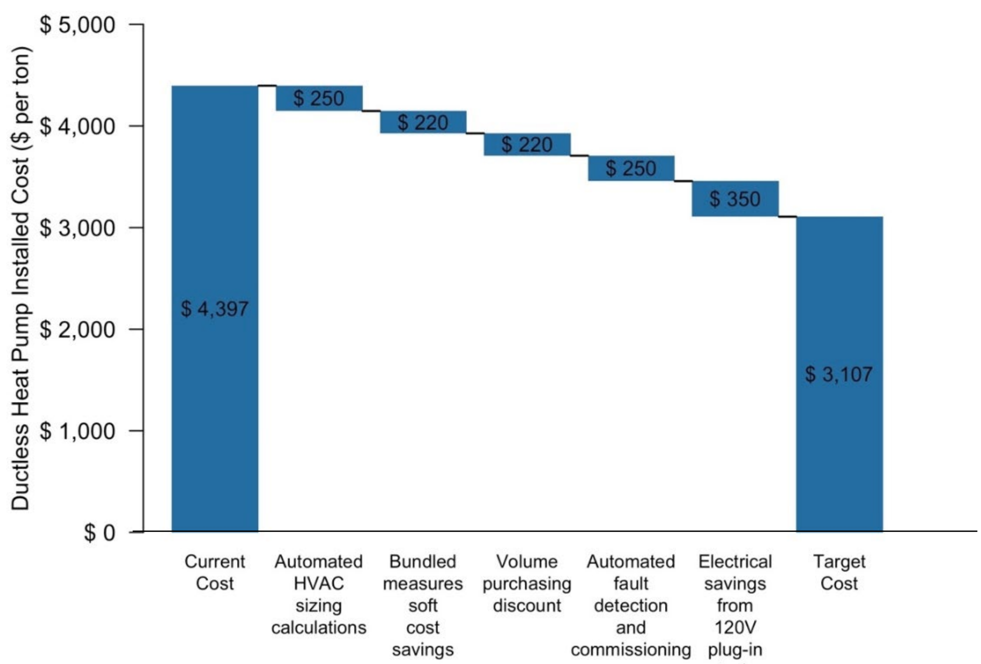


Figure 74. Example cost compression of ductless heat pump technologies. Estimated, non-validated cost reductions pictured.

Finally, power efficient appliances are being developed that can operate using existing 120V outlets throughout a home, most importantly for heat pump water heating and heat pump space conditioning. Plug-in heat pump water heaters are being tested by the New Buildings Institute, and a recent webinar on that work suggests that most manufacturers may offer 120V plug-in models in a year or two. 120V heat pumps for space conditioning are further from market development, but at least one example, the Anova PTAC through-the-wall unit will operate by 120V plug. Other options include non-permanent technologies, such as portable air conditioners and heat pumps. Generally, these have low efficiency compared with standard equipment, so energy costs are a real concern in many locations.

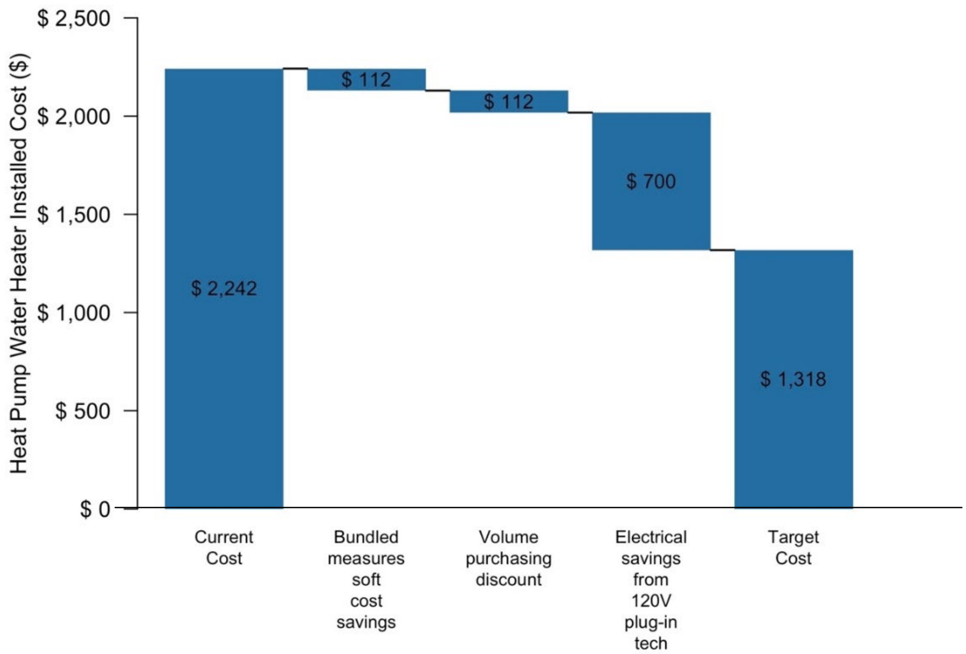


Figure 75. Example cost compression of 50-gallon heat pump water heater. Estimated, non-validated cost reductions pictured.

12.3 Business Economics

The companion literature review to this study (Less et al., 2021) found that gross margins (i.e., soft costs, overhead, profit) were higher than industry averages for home performance contractors—47% on average. This gross margin is compared with other construction industry benchmarks in Figure 76. Three of the benchmarks represent standard residential remodeling, with an average gross margin of 33% (CSI Market, 2020; Freed, 2013; National Association of Home Builders, 2020). The non-residential or new construction benchmarks are considerably lower, 10-26%. This suggests that if energy upgrade businesses were to reduce gross margins to the level of standard remodeling, overhead and profit costs could be reduced from 47 to 33%, a 14% reduction in project cost.

To reduce gross margins in energy upgrade work, it is necessary to understand what common soft costs are and how much they typically cost. In their deep retrofit market survey, (Chan et al., 2021) reported typical soft costs in deep retrofit projects, including design costs, testing, etc. These average soft costs are shown in Figure 77. The survey showed that, while not common to all projects, professional services from architects was a very high cost item (nearly $10,000 per project). More commonly reported items were home inspections/energy audits and HVAC load sizing (about $600 each per home); travel and customer management (about $800 each per home); and less expensive items, such as HVAC commissioning and envelope leakage measurements (<$200 each per home).

Chan also reported on average labor rates for different energy upgrade soft cost activities, and the mean values ranged from $90 to $138 per hour. Typical hours spent on each soft cost category were also estimated, and these varied from roughly 1-hour (diagnostics for combustion, ventilation flow and IR imaging) up to 12- or 13-hours per project (travel to/from jobsite, project management). The data presented in Figure 77 suggest that streamlining project management, planning/design and delivery likely have high potential for savings, whereas diagnostics, testing and permits likely have relatively lower potential, due to their low costs.

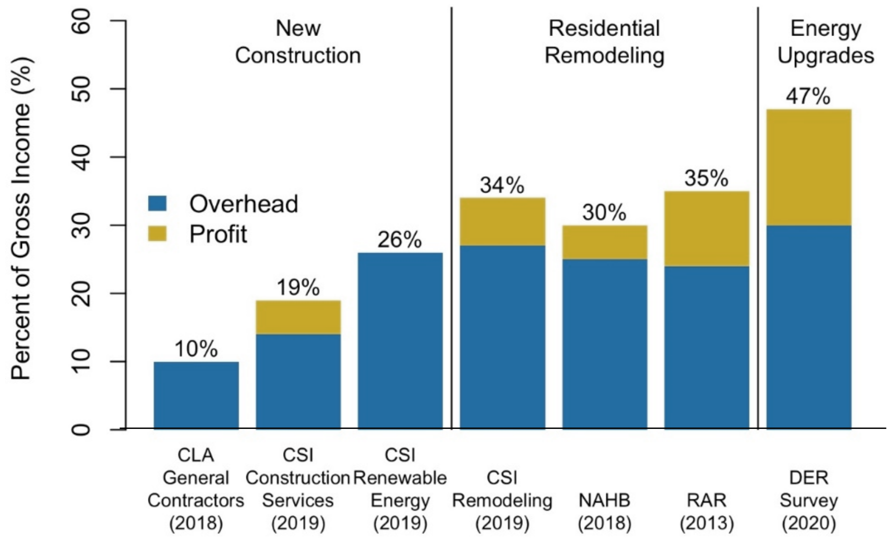


Figure 76. Comparison of gross margins (overhead + profit) for deep retrofits compared with other construction sectors. From: (Less et al., 2021).

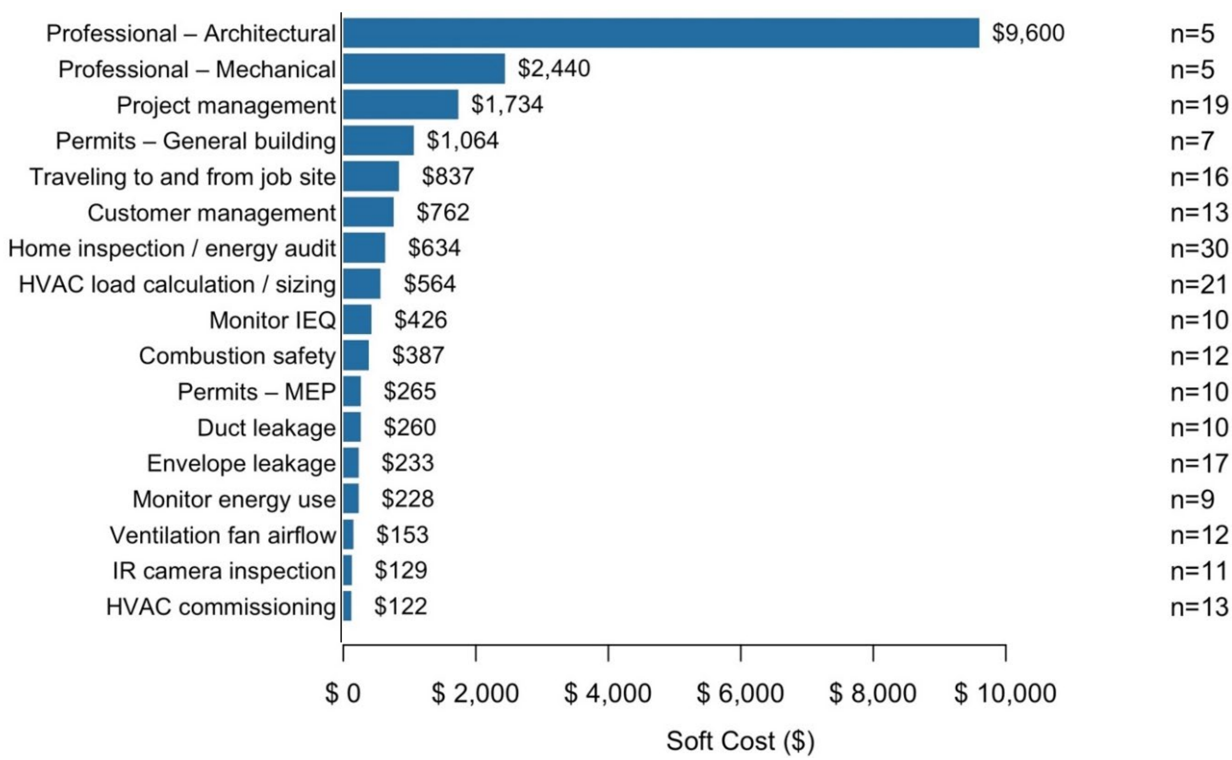


Figure 77. Average project soft costs reported in deep retrofit industry survey, (Chan et al., 2021)

(Less et al., 2021) suggested the following opportunities and estimates for reducing soft costs in home performance upgrades:

- **Outsource customer acquisition to programs with marketing and sales expertis**e. Customer acquisition typically costs $1,000 to $1,600 per project, and up to $2,500. With lower cost labor and use of best practices, this cost can be reduced to around $700 per project.
- **Reduce diagnostic testing and commissioning.** Combustion safety testing is typically $387 per project, but electrification of all end-uses could eliminate the need for this testing.
- **Use remote approaches to customer acquisition, management and sales.** Remote audits can reduce audit costs by 40% for individual projects, and by 60% for projects that execute the work scope. Estimated at 20-hours and $1,000 saved per executed project.
- **Automated, rapid HVAC equipment sizing.** Current HVAC sizing costs are typically $564, which can currently be reduced using rapid, block load software programs. In the future, there is potential for further reduction through automated smart meter or connected thermostat data analytics.

While gross margins are roughly half the total project costs in a deep energy retrofit, there were few soft cost details gathered in the database. These were limited to program administration, permitting and health & safety work. Program administration costs were the most expensive, at $714 per project. These costs are highly variable by program. Building permits were relatively low-cost, with typical permitting costs of $280, ranging from $100 to $600. (Chan et al., 2021) reported that permit costs were $1,064 for general building and $264 for mechanical, electrical and plumbing (MEP) permits. Health and safety (H&S) measures are primarily combustion safety testing, with median costs of $109 per project. Chan et al. reported that combustion safety testing costs averaged $387. H&S measures in the database may have been for programs with different testing requirements that were less detailed and time-consuming. While still ensuring occupant safety, reducing such testing requirements is one way to reduce project soft costs. An example of achieving this aim would be to electrify a home's heating and hot water, thus removing the need for a combustion safety test.

12.4 No and Low-Cost Efforts

Lighting upgrades, appliance change-outs and other baseload reductions and plug load management strategies can provide substantial energy savings on the order of 10% at little to no cost. They should always be considered step-one in any successful upgrade project at the very least to pad a package with low-cost, high-return measures that help improve the payback rate of higher cost measures. For example, the Home Energy Analytics Home Intel program in California's Bay Area supports energy savings based on household operational changes that are made in response to behavioral and retro-commissioning feedback generated in part by automated smart meter analytics, along with input and suggestions by remote energy coaches. This program has achieved meter-validated savings averaging 10% across more than 1,400 homes enrolled in the program. Energy reductions of 10% at little-to-no-cost have the ability to substantially increase the performance and outcomes of more comprehensive energy upgrade projects.

Some technologies are taking this operational approach a step further and are providing automated control of building loads in order to reduce carbon emissions or reduce grid stress. One important example is automated emissions reductions (Auto AER) from WattTime, which is a control strategy that leverages internet-connected end-uses along with real-time estimates of electrical grid carbon intensity to automatically operate existing appliances in a way that reduces carbon emissions. Analysis done in conjunction with RMI suggests that using current technologies, automated load reduction can achieve 5% CO_2 reduction for cooling equipment and 12-15% reductions for heat pump water heaters or electric cars (which have more flexible load potential) (Mandel & Dyson, n.d.). Mandel & Dyson claim that with improved methods to measure marginal grid emissions, reductions increase upwards of 40%. Similar smart devices may be able to schedule energy using appliances during off-peak hours, which can substantially reduce household energy costs. An example of this capability is provided by the demand response company Ohm Connect[18], which compensates participants for shedding electrical load during select periods of grid stress. Numerous smart devices, including smart plugs, internet connected thermostats and others can be integrated and centrally controlled during load shed events. In addition, including some of these low-cost technologies in retrofit packages can augment carbon and cost savings opportunities for consumers, and can better guarantee savings.

[18] https://www.ohmconnect.com/

REFERENCES

2018 IECC, 2017. (2017). *2018 International Energy conservation Code (IECC)*. International Code Council.

Armstrong, S., Higbee, E., Anderson, D., Bailey, D., & Kabat, T. (2021). *Pocket Guide to Home Electrification Retrofits*. Redwood Energy.

ASHRAE 62.2. (2019). *Standard 62.2-2019: Ventilation and Acceptable Indoor Air Quality in Residential Buildings*. ASHRAE.

Bay Area Renewable Energy Network. (2018). *Details on R-PACE fees and interest rates as of May 2018*. Bay Area Renewable Energy Network. https://63bce253-fb1e-40fd-9fe6-f6631fc8865f.filesusr.com/ugd/1ef210_4fd6abdd3ba745c1b829cf9e09ac6953.pdf

Billingsley, M. A., Hoffman, I., Stuart, E., Schiller, S. R., Goldman, C. A., & LaCommare, K. (2014). *The Program Administrator Cost of Saved Energy for Utility Customer-Funded Energy Efficiency Programs* (LBNL-6595E). Lawrence Berkeely National Laboratory. https://www.osti.gov/servlets/purl/1129528/

Chan, W. R., Less, B. D., & Walker, I. S. (2021). *DOE Deep Energy Retrofit Cost Survey*. Lawrence Berkeely National Laboratory. https://doi.org/10.20357/B7MC70

CSI Market. (2020, July 20). *Home Improvement Industry Profitability by quarter, Gross, Operating and Net Margin from 2 Q 2019*. CSIMarket.Com. https://csimarket.com/Industry/industry_Profitability_Ratios.php?ind=1306&hist=4

Freed, S. (2013, December 19). *Check Your Vitals: Remodeling Benchmarks | Remodeling*. Remodeling.Hw.Net. https://www.remodeling.hw.net/benchmarks/check-your-vitals-remodeling-benchmarks

Goldman, C. A., Hoffman, I., Murphy, S., Mims Frick, N., Leventis, G., & Schwartz, L. (2020). The Cost of Saving Electricity: A Multi-Program Cost Curve for Programs Funded by U.S. Utility Customers. *Energies*, *13*(9), 2369. https://doi.org/10.3390/en13092369

Holladay, M. (2012). *The High Cost of Deep-Energy Retrofits | GreenBuildingAdvisor.com*. http://www.greenbuildingadvisor.com/blogs/dept/musings/high-cost-deep-energy-retrofits

IEA. (2014). *Capturing the Multiple Benefits of Energy Efficiency* (p. 232). International Energy Agency.

Lane, T. (2019). *Contractor's Pricing Guide: Residential Repair & Remodeling Costs with RSMeans data 2020*.

Less, B. D., & Walker, I. S. (2014). *A Meta-Analysis of Single-Family Deep Energy Retrofit Performance in the U.S.* (No. LBNL-6601E; p. 60). Lawrence Berkeley National Lab. https://doi.org/10.2172/1129577

Less, B. D., Walker, I. S., & Casquero-Modrego, N. (2021). *Emerging Pathways to Upgrade the US Housing Stock: A Review of the Home Energy Upgrade Literature*. Lawrence Berkeley National Lab. https://doi.org/10.20357/B7GP53

Mandel, J., & Dyson, M. (n.d.). *WattTime Validation and Technology Primer*. Rocky Mountain Institute. Retrieved June 16, 2021, from https://www.watttime.org/app/uploads/2019/03/Automated-Emissions-Reduction-Primer_RMI-Validation_June2017.pdf

National Association of Home Builders. (2020). *Remodelers' cost of doing business study*. http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=2355104

Navigant Consulting, Inc. (2018a). *Water Heating, Boiler, and Furnace Cost Study (RES 19)* (No. 183406). The Electric and Gas Program Administrators of Massachusetts Part of the Residential Evaluation Program Area. https://ma-eeac.org/wp-content/uploads/RES19_Assembled_Report_2018-09-27.pdf

Navigant Consulting, Inc. (2018b). *Ductless Mini-Split Heat Pump Cost Study* (Final Report RES 28). The Electric Program Administrators of Massachusetts Part of the Residential Evaluation Program Area. https://ma-eeac.org/wp-content/uploads/RES28_Assembled_Report_2018-10-05.pdf

NREL. (2020). *Solar Installed System Cost Analysis*. https://www.nrel.gov/solar/solar-installed-system-cost.html

US Environmental Protection Agency (EPA). (2019). *CO_2 Equivalent Total Output Emission Rate (lb/MWh) by State*. EGRID Data Explorer. https://www.epa.gov/egrid/data-explorer

US Environmental Protection Agency (EPA). (2020). *EGRID2018 Summary Tables*. EGRID2018 Summary Data. https://www.epa.gov/sites/production/files/2020-01/documents/egrid2018_summary_tables.pdf

Zhu, Y., Connolly, R., Lin, Y., Mathews, T., & Wang, Z. (2020). *Effects of Residential Gas Appliances on Indoor and Outdoor Air Quality and Public Health in California* (No. 20184996). UCLA Fielding School of Public Health. https://ucla.app.box.com/s/xyzt8jc1ixnetiv0269qe704wu0ihif7

APPENDIX A – Database Structure

The structure of the project cost database tables and sub-tables is shown in Figure A 1, including Project, Energy, Measure, Source and Performance tables. Each of these is described in greater detail below.

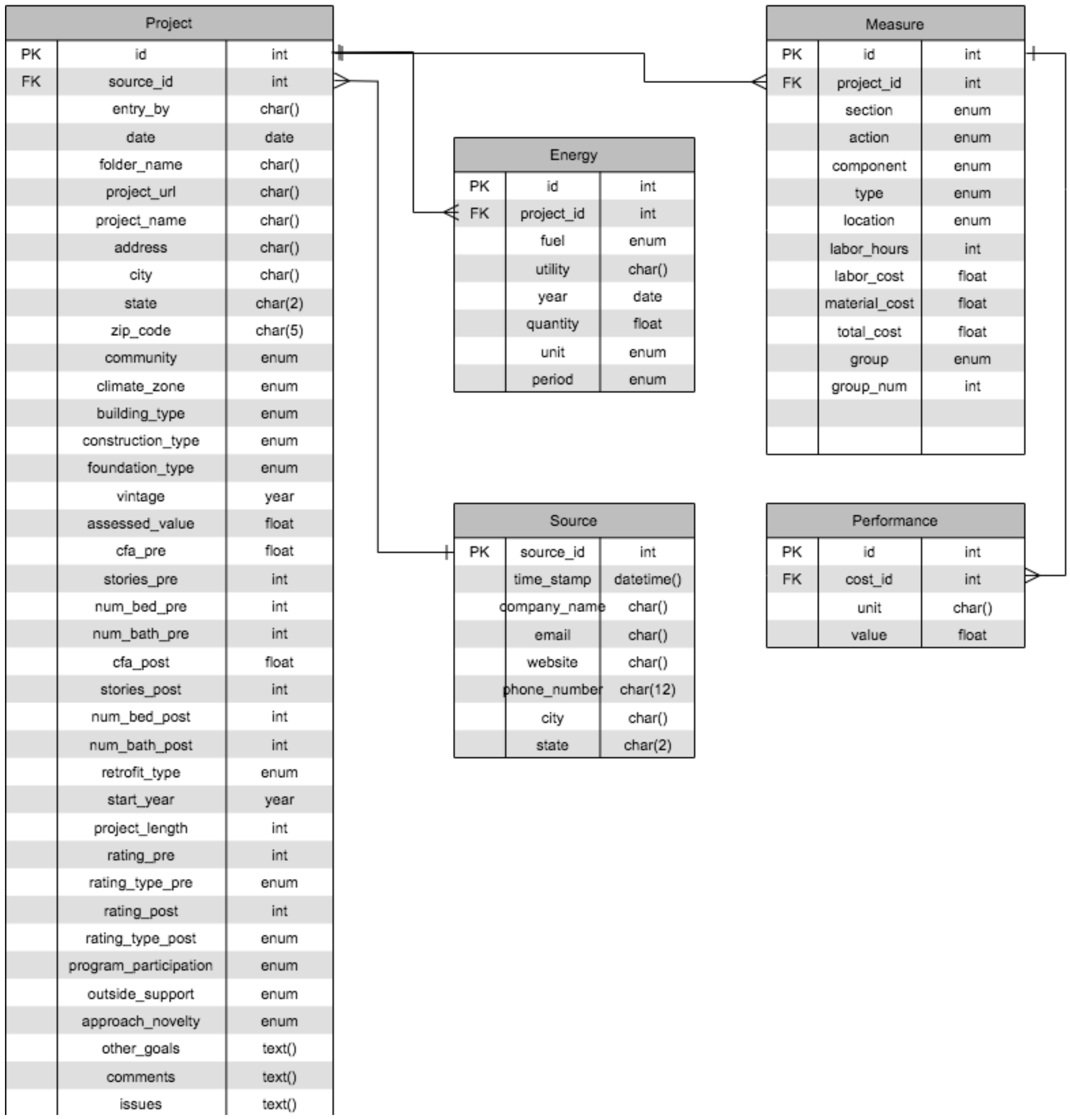


Figure A 1. DER cost stack database entity relationship diagram.

A.1 Project Table

The project table has 39 fields and contains the metadata for each project, including information about the building characteristics (e.g., location, size, age) and the type of retrofit performed (e.g., program participation, support, approach, goals). The table also contains reference information such as the project ID and name, when and by whom the data was entered, and where the project documents are stored on LBNL file systems. It references one parent table (Source), which stores information about the contractor or organization that provided the project information. The data entry fields are enumerated in the tables below. Table A 1 highlights the primary data fields that characterize the project at the highest level, including project location and metadata fields. Table A 2 provides building characteristic entries, including construction type, vintage, etc. Finally, the retrofit is characterized at a high level in Table A 3, including project date, duration, type, etc. The primary and secondary retrofit types (e.g., HVAC-focused, Envelope-focused, etc.) are further described in Table A 4.

Table A 1. Project table primary fields.

Field	Description	Type / Range / Options
Source	Source of data	Picklist (from Source table)
Data entry by	Name of data entry person	Picklist
Project folder URL	URL of Google Drive project folder	URL
Street address	Address of project	Free text entry
City	City where project is located	Free text entry
State	State where project is located	Picklist
Zip Code	Zip Code of project location	5-digit Zip Code
Community	Type of community	Urban, Suburban, Rural

Table A 2. Project table building characteristics fields.

Field	Description	Type / Range / Options
Building type	Type of building that was retrofitted	Single family detached, Single family, attached, Townhouse, Apartment, Condominium, Mobile home, Manufactured home, Other, Unknown
Construction type	Primary construction	Wood frame, Brick, CMU, Other, Unknown
Foundation type	Primary foundation type	Slab-on-grade, Crawl space, Basement, Split level, Mixed Slab-on-grade and Crawl space, Mixed Slab-on-grade and Basement, Mixed Crawl space and Basement, Other, Unknown
Vintage	Year the home was built	1800 - 2020
Assessed value	Current value of the home	\$0 - \$5,000,000
Conditioned floor area (Pre and Post)	Total interior conditioned floor area including finished basements	Square feet (200 - 10,000)
Stories (Pre and Post)	Number of floors above grade	1 - 5
Number of bedrooms (Pre and Post)	Number of bedrooms	1 - 10
Number of bathrooms (Pre and Post)	Number of bathrooms and half-baths	1 - 10 by 1/2

Table A 3. Primary and secondary retrofit descriptions.

Field	Description	Type / Range / Options
Primary retrofit type	The primary focus of the retrofit	Superinsulation, Home Performance Upgrade, Individual measure, Over-time, HVAC-focused, Envelope-focused, Aligned with Other Remodeling or Addition, All-electric, DIY, Small commercial, Aggregated pricing, Book pricing
Secondary retrofit type	The secondary focus of the retrofit	Same as above
Project start	Year project began	1980 – 2020
Project length	How long the project took	1 – 100 (months)
Pre-rating	Rating of home before this project	HERS, Home Energy Score, or Other
Post-rating	Rating of home after this project	HERS, Home Energy Score, or Other
Program participation	What program this project was part of if any	CA CPUC - Energy Upgrade CA CA HEA – HomeIntel CA MTC - BayREN Home+ CA Program A GA Southface - GoodUse MA DOER – Home MVP MN CEE - Program A NY NYSERDA - Deep Retrofit Pilots TN/NC - EEtility PAYS USA ACI - Thousand Home Challenge U.S. DOE - Building America Research VT New Leaf Design - Zero Energy Now
Outside support	Who provided support	None, Utility, State energy program, DOE, EPA, Other
Novelty of approach		Standard, Semi-custom, Fully-custom
Other performance goals / Achievements		Free text entry
General comments		Free text entry
Problems / Issues		Free text entry

Table A 4. Primary and secondary retrofit descriptions

Retrofit Type	Description
Superinsulation	Envelope upgrades that are significantly above code minimum. Examples would include double-stud walls, R60 roof, triple pane windows. Typical for Passive House retrofits, or cold climate projects from the NYSERDA or MASS SAVE pilots.
Home Performance Upgrade	Uses typical approaches to achieve whole dwelling energy savings. Off-the-shelf equipment and strategies, but comprehensively applied.
Individual Measure	Only use this for a project that covers single measures, rather than whole home projects. For example, just exterior wall insulation upgrades or advanced HVAC upgrades. Also used for Aggregated and Book pricing entries as the Primary retrofit type.
Over-Time	Characterized by an over-time implementation approach.
HVAC-Focused	Whole-house upgrade where the most effort and budget are dedicated to HVAC upgrades. Mostly HVAC, some envelope and other upgrades.
Envelope-Focused	Places most focus on envelope upgrades and might include less intensive HVAC upgrades. For example, only duct sealing or equipment tuning, paired with thorough envelope upgrades.
Aligned with Other Remodeling	Clearly part of a much larger remodel to the home, including additions, replacement of finishes, changes in interior layout, etc.
All-Electric	Focus is on fuel switching to electricity
DIY	Implemented primarily by the owner
Small Commercial	Small commercial retrofit of a residential construction building
Aggregated Pricing	Average program or contractor costs of a large number of individual measures. Only enter this as the Secondary retrofit type.
Book Pricing	Contractor book pricing used for estimating individual measures. Only enter this as the Secondary retrofit type.

A.2 Energy Table

Each row of the Energy table contains information about the energy use of a project. As many rows as needed can be used to record data from utility bills, modeling, or savings estimates, and they can be for the pre- or post-retrofit use or savings. Again, the energy data table was designed to promote maximum flexibility to ingest whatever information was available from any given project or source. This included a wide variety of fuel types, energy units, and performance periods. The energy data is linked to the project data using a project ID. Data fields for the Energy table are shown in Table A 5. Post-processing of the energy data table is described further in

Table A 5. Energy table fields

Field	Description	Type / Range / Options
Fuel	Type of fuel used	Electricity, Natural gas, LPG, Fuel oil, Wood, All, Other
Source	Source of data	Free text entry. “Model” if from simulation. “Actual” if from real bill data
Year	Year the data are from	1990 - 2020
Quantity	Annual quantity	-100,000 - 100,000 (where negative values indicate energy generation)
Unit	Unit used for this quantity	kWh, Therms, Gallons, Cords, %, $
Period	When the data are from	Pre, Post, Post (net PV), Savings

A.3 Measure Table

Each row of the Measure table contains 16 fields that describe a step that was taken as part of a retrofit project (see Table A 6). The measure can be as simple as installing a light bulb, or as complex as insulating and sealing the entire building envelope. Each measure is described using three required fields:

- **Section** defines in what section of a typical job order the work was performed. The Section can be one of ten options (see Table A 6).
- **Action** describes the action or type of work performed for this measure, and the possible values are dependent on the section selected. For example, the Walls Section can have actions that include: frame, install, insulate, paint, and seal.
- **Component** is the object to which the action is directed, and the possible values are dependent on both the component and the action selections. For example, installing a furnace would be HVAC/Install/Heating, while insulating a wall would be Walls/Insulate/All.

These unique sets of Section/Action/Component make up a list of over 200 possible base measures. Each measure can be further refined by a set of possible types (e.g., Condensing for the furnace, or fiberglass batt for the wall insulation) and locations (e.g., Basement for the furnace, and cavity for the insulation). Each measure can also be characterized by a set of Performance/Units pairs. The performance is a number and the units identify how the performance is measured (e.g., 93% AFUE for the furnace and 13 R-value for the wall insulation).

Measures can have costs or be strictly informational. For example, if a project includes the total insulation cost for the whole house as a single line item, while also providing details about the foundation, wall and attic insulation (but not their itemized costs), then the insulation measures would be entered as information with no costs associated, because they provide informative detail that we cannot just infer from the whole house insulation entry with the cost entered.
Two fields, Group and Group number, are used to associate separate measure entries, either within one or across multiple Sections. The “Primary” Group indicator is used for the entry that overall best-characterizes a group of measures with the same Group number. The Primary measure of a group will always have a cost entered. The “Secondary” Group indicator is used for all the other measures with the same Group number. Secondary measures may or may not have costs entered. Use of the grouping features depends on whether the grouped measures are in the same or in different Sections.

- **Same Section**: Measures in the same section are grouped if a single cost is provided but the individual measures do not have costs. For example, Appliance/Install/All would be used to record the cost of all appliances, and be marked as Primary, and all specific appliances would be assigned the same Group number and entered as Secondary measures without costs.

- **Different Sections:** Measures in different sections are grouped if the work is related, regardless of cost data. For example, an HVAC install that included explicit cost data for electrical work, framing in the attic and the HVAC equipment itself would fall into three different Sections, but they are all effectively required as part of the HVAC work and the three entries would be assigned a single Group number. Since this is an HVAC replacement the entry in the HVAC Section would have Group set to Primary, and the framing and electrical entries would have the Group set to Secondary.

The cost for a specific measure is recorded using four fields: Labor hours, Labor cost, Materials cost, and Total cost. If any labor or materials costs are entered, then the total cost is also entered.

Table A 6. Measure table fields.

Field	Description	Type / Range / Options
Section	Part of the dwelling the measure applies to	Appliance, Attic, Doors, Electrical, Foundation, House, HVAC, Plumbing, Walls, Windows
Action	What was done	Depends on Section
Component	Building component, the Action was done to	Depends on Action
Type	Adds details about the Component (e.g., type of insulation or windows)	Depends on Component
Location	Used for Insulate and Install measures only. For Insulate it refers to where in the building envelope the insulation is installed. For Install it is where the Component is installed.	Depends on Action. **Insulate:** Inside, Outside, Cavity **Install:** Attic, Basement, Crawlspace, Garage, Closet, Conditioned space
Performance (3)	Performance indicators for the measure such as quantity or efficiency, up to three	Number
Units (3)	Units of the measure performance, up to three	Depends on Measure
Labor hours		0 - 1000
Labor cost	Include "Subs" costs in labor, if provided	\$0 - \$100,000
Materials cost		\$0 - \$100,000
Total cost	This should include both the Labor and Materials costs	\$0 - \$500,000
Group	Used to connect measures together that form part of a larger scope	Primary, Secondary
Group number	All measures in a group should have the same number	1 - 10
Weight	The number of houses this cost represents. Should be 1 except for Aggregated price data.	1 - 1000
Pre-condition	The pre-retrofit condition of the Component before the measure was applied	Free text entry
Notes	Additional information about the measure	Free text entry

APPENDIX B – Energy Unit Conversion

Site energy data entries for all energy units were converted to a common unit of MMBtu using the conversion factors in Table B 1.

Table B 1. Conversion units for site energy.

Energy Unit	Multiplier to MMBtu	Source
Therm	100,000 / 1,000,000	
kWh	3,412 / 1,000,000	
kBtu/ft^2-yr	ft^2 / 1,000	
Cubic feet of natural gas	103,700 / 1,000,000	https://www.eia.gov/tools/faqs/faq.php?id=45&t=8
Cord of fire wood	20	https://www.eia.gov/energyexplained/units-and-calculators/british-thermal-units.php
Gallon of LPG	91,452 / 1,000,000	https://www.eia.gov/energyexplained/units-and-calculators/
Gallon of Fuel Oil	137,381 / 1,000,000	https://www.eia.gov/energyexplained/units-and-calculators/
Ton of wood pellets	13.6	https://www.fpl.fs.fed.us/documnts/techline/fuel-value-calculator.pdf

All site energy data was converted to USD using conversion factors listed below in Table B 2 (see state average natural gas and electricity retail prices in Table B 3). Energy cost data was not adjusted for inflation to common 2019 USD, because most energy costs were reported without the year being recorded.

Table B 2. Conversion factors for energy cost.

Energy Unit	Multiplier to USD$	Source
Therm	State Mean $/therm (2019), see Table B 3	https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PRS_DMcf_a.htm
kWh	State Mean $/kWh (2019), see Table B 3	https://www.eia.gov/electricity/state/
kBtu/sf-yr.	NA	
Cubic feet of natural gas	(103,700 / 1,000,000) x State Mean $/therm (2019)	
Cord of fire wood	150	https://www.bankrate.com/mortgages/how-much-does-a-cord-of-wood-cost/
Gallon of LPG	2.181	https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=M_EPLLPA_PRS_NUS_DPG&f=M (Average of 2019 values)
Gallon of Fuel Oil	2.146333	https://www.eia.gov/dnav/pet/pet_pri_wfr_a_EPD2F_PRS_dpgal_w.htm
Ton of wood pellets	250	https://homeguides.sfgate.com/much-cost-run-pellet-stove-67241.html

All site energy data was converted to equivalent carbon emission (CO_2e) using conversion factors listed below in Table B 4. State mean CO_2e emission rates for delivered electricity were retrieved from the U.S. EPA's eGRID data set for year 2018 (US Environmental Protection Agency (EPA), 2020). The emission factors for each state are included in Figure B 1. Note, these are the average total output emission factors for the delivered electricity in each state. They do not reflect the short- or long-term marginal emission rates for loads added to (or removed) from the grid at any given moment in time. The marginal emissions (also included in the eGRID dataset) are roughly double these average values.

Table B 3. State mean retail prices for natural gas and electricity, 2019 data. [Retrieved from eia.gov]

State	Residential Annual Price ($/MMBtu) 2019	Average retail price ($/kWh) 2019
Alabama	15.63	0.0983
Alaska	11.11	0.2022
Arizona	13.49	0.1052
Arkansas	11.05	0.0822
California	12.95	0.1689
Colorado	7.77	0.1017
Connecticut	14.61	0.1866
Delaware	12.1	0.1052
District of Columbia	12.81	0.1227
Florida	21.73	0.1044
Georgia	14.87	0.0986
Hawaii	44.14	0.2872
Idaho	6.5	0.0789
Illinois	8.04	0.0956
Indiana	8.68	0.0991
Iowa	8.19	0.0908
Kansas	9.24	0.1026
Kentucky	10.85	0.0861
Louisiana	11.51	0.0771
Maine	16.05	0.1404
Maryland	12.55	0.1124
Massachusetts	14.72	0.184
Michigan	8.08	0.1156
Minnesota	8.06	0.1033
Mississippi	10.77	0.0928
Missouri	10.41	0.0968
Montana	7.09	0.0902
Nebraska	7.9	0.0908
Nevada	9.5	0.0878
New Hampshire	15.75	0.1715
New Jersey	9.73	0.1342
New Mexico	6.4	0.0899
New York	12.61	0.1434
North Carolina	12.88	0.0945
North Dakota	7	0.0885
Ohio	9.58	0.0958
Oklahoma	9.4	0.0786
Oregon	9.97	0.0881
Pennsylvania	11.7	0.0981
Rhode Island	15.36	0.1849
South Carolina	13.14	0.1002
South Dakota	7.29	0.0996
Tennessee	9.45	0.0969
Texas	10.61	0.086
Utah	7.82	0.0824
Vermont	13.14	0.1536
Virginia	12.62	0.0952
Washington	9.82	0.0804
West Virginia	9.9	0.0849
Wisconsin	7.68	0.1066
Wyoming	8.06	0.081
U.S.	**10.51**	**0.1054**

Table B 4. Conversion factors for energy cost.

Energy Unit	Multiplier to MMBtu	Source
Therm	117.00 / 10	---
kWh	State Mean Total Emission Output Factors, eGRID 2018 (US Environmental Protection Agency (EPA), 2020)	---
kBtu/ft²-yr.		---
Cubic feet of natural gas	(103,700 / 1,000,000) x 117.00	---
Cord of fire wood	0	The U.S. EPA recognizes burning forest biomass as carbon neutral, but many disagree with this assessment.
Gallon of LPG	12.70	---
Gallon of Fuel Oil	22.40	---
Ton of wood pellets	0	---

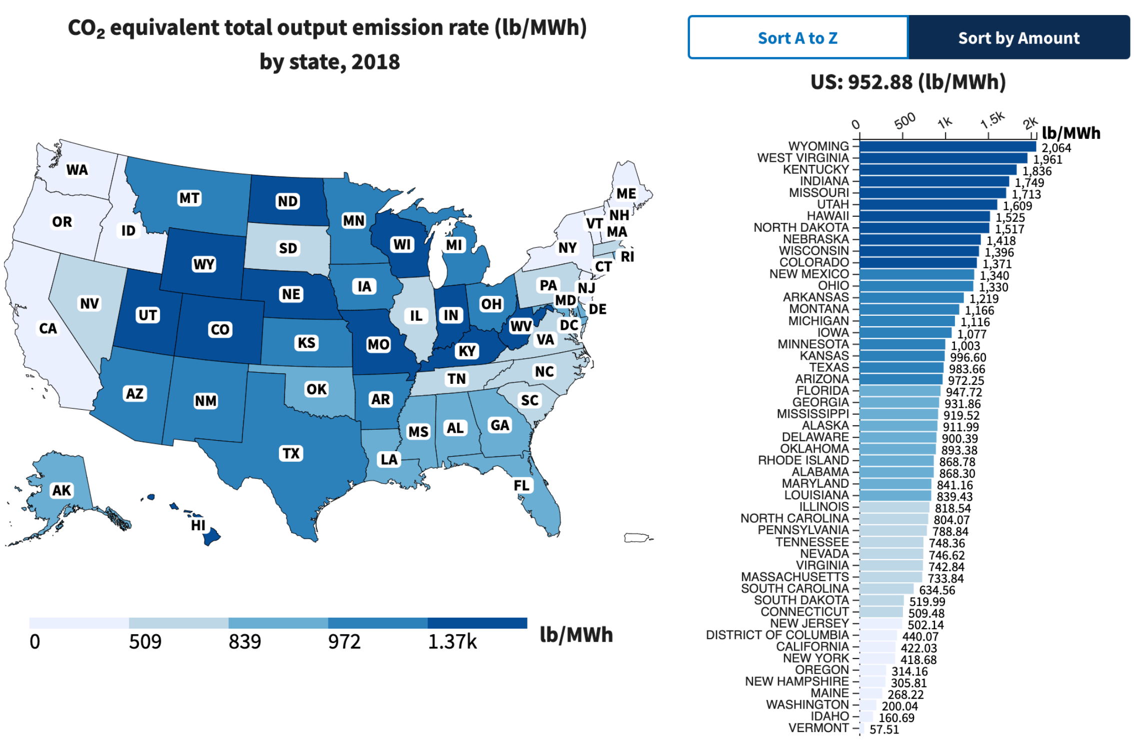


Figure B 1. Carbon dioxide equivalent (CO_2e) total output emission rate (lbs./MWh) for delivered electricity in each US state for year 2018 (US Environmental Protection Agency (EPA), 2019)

APPENDIX C – Regression Modeling

Each regression model was built using all variables recorded for that set of measures. For individual measures where a value was not recorded (e.g., SEER rating of an air conditioner), the missing values were imputed using the median value of that variable across all projects. Without this median imputation, most measures would be excluded from the model prediction due to missing values. Use of the median value cancels out any contribution from a project to the variance associated with the variable in question, while still allowing the measure to be included in the model.

For each model, we implemented versions that were geographically/location aware (predictor variables included program, climate zone, etc.) for determining variable importance, and those that were not aware (those variables were excluded) for making general predictions. The variables included in each model type are shown in Table C 1. As noted above, all models included the measure features and description (e.g., ductless heat pump, SEER 20). We use the non-aware models for prediction of costs and energy savings in the archetypal upgrade projects, which are intended to be general and not location-specific. We use the location aware models expressly for determining variable importance as an aid in understanding which features of a project or measure were important in determining its cost. In these models, location information was included in the predictor variables, because they might play an important role in cost variability.

Table C 1. List of non-measure features included in each regression model type.

Location Aware Models	Location Unaware Models
program_particiation	---
Climate.Zone	---
cfa_post	cfa_post
stories_post	stories_post
start_year	start_year
Vintage20	Vintage20
retrofitType	---

For both modeling exercises, several different statistical model types were assessed for each prediction, in order to identify the model with the lowest prediction errors (i.e., root mean squared error (RMSE)). Models included multi-variate linear regression, random forest regression, elastic net, ridge and lasso regression. In nearly all cases, including both the measure prediction models and energy savings prediction models, the random forest regression had the best performance (i.e., lowest RMSE and highest adjusted R^2). For example, when comparing multi-linear regression with random forest for predicting net-site energy savings, the RMSE was 12.2% (adjusted R^2 0.578) for random forest and 386% for multi-linear regression (adjusted R^2 0.062). The problem of predicting energy savings is highly non-linear in the database, so all models except random forest performed poorly. In most cases of predicting measure costs, the performance was more comparable between linear and non-linear models, but random forest was consistently the best or amongst the best. For this reason, we have defaulted throughout this report to reporting cost and energy predictions based on the random forest regressions.

Cross-validation is used to limit over-fitting in machine learning models. Over-fitting occurs when a model precisely predicts data used in building the model but performs poorly on new/novel data. These over-fit models are highly biased to the training data and do not generalize well. The cross-validated RMSE values were used to assess each model. The RMSE values represent the typical prediction errors (in the same units as the outcome variable) when a prediction model is applied to measures not used in generating the model parameters. For the prediction models, cross-validation was performed using ten-folds, repeated five-times. In practice, this means the entire dataset is subdivided into ten equal sized segments, and the regression model is built using nine of the segments, while one segment is held out. The resulting regression model is used to predict the hold out segment that was not included in the model's training data. The error (RMSE) is then computed for these hold out predictions. Each of the ten segments is used as the hold out set once, and this whole process is repeated five-times. The RMSE values (and adjusted R^2 values) are then averaged across the 50 iterations.

Variable importance was determined using a recursive feature elimination algorithm that leverages the random forest regression model (*rfe function*[19] in caret machine learning package). This rfe algorithm identifies the optimal set of features/variables to include in the prediction model. Based on the model using the optimal features, the caret *varImp function*[20] is then applied to assess which variables are most important to predicting the outcome. "Importance" is determined by the incremental mean squared error (MSE) as follows: "the MSE is computed on the out-of-bag data for each tree, and then the same computed after permuting a variable. The differences are averaged and normalized by the standard error." In practice, this means that for each predictor variable in the model, the prediction accuracy is compared between two scenarios: first, using the actual training data for that variable; and second, using a permuted (i.e., randomly mixed up) version of that variable's training data. If the prediction accuracy changes substantially when a variable is randomly permuted, then that variable is interpreted as important to the model's predictions. But if the prediction accuracy does not change very much when a variable is randomly permuted, then it is not considered an important variable. Variables are ultimately ranked by the change in MSE that occurs when that variable's values are randomly mixed up.

[19] https://topepo.github.io/caret/recursive-feature-elimination.html
[20] https://www.rdocumentation.org/packages/caret/versions/6.0-86/topics/varImp

APPENDIX D – Cluster Cost Stacks

This appendix summarizes all the cost stacks for the projects subdivided into the six clusters identified in the analysis.

D.1 Low-Cost Weatherization

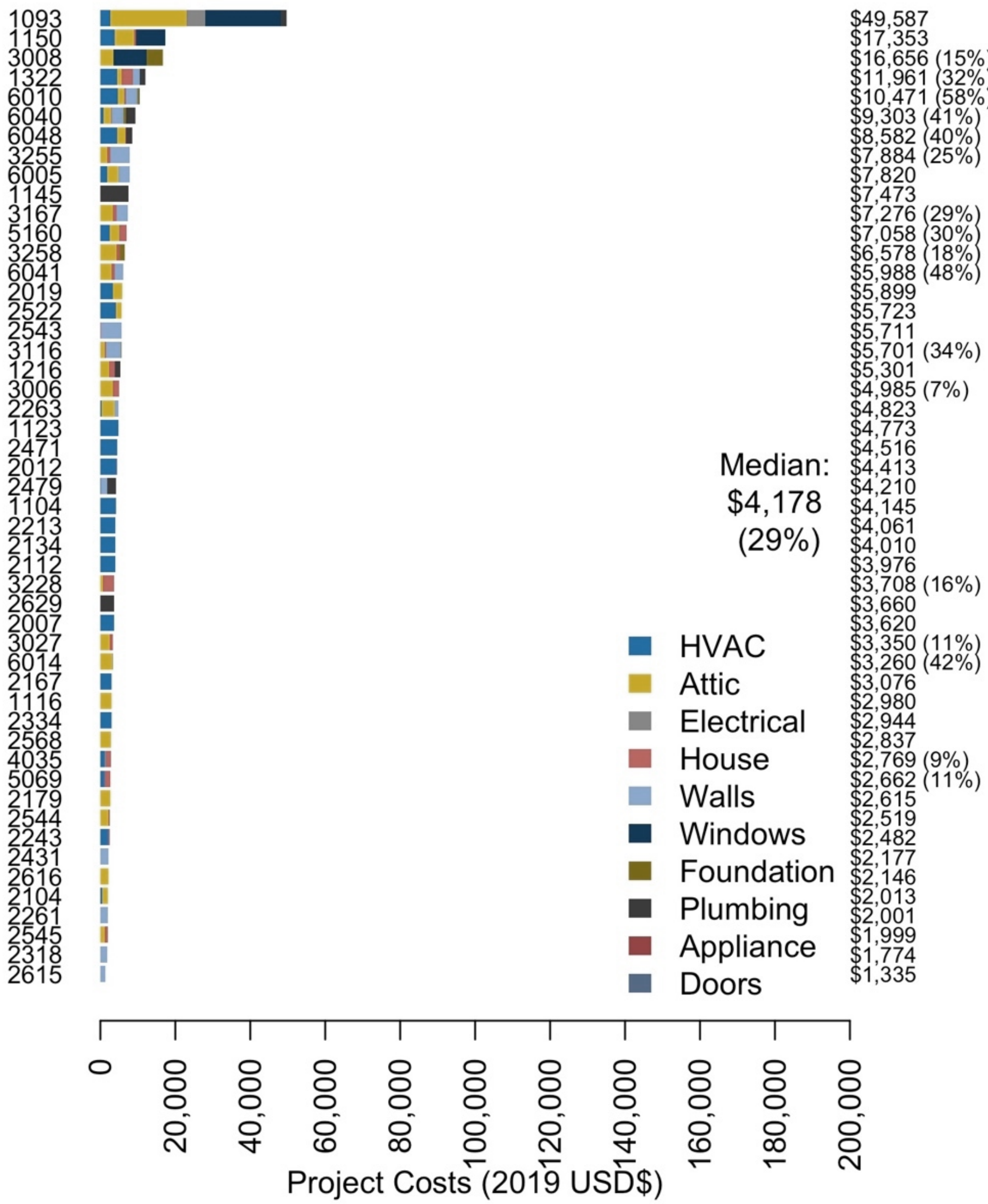


Figure D 1. Basic: Project Costs - Carbon.

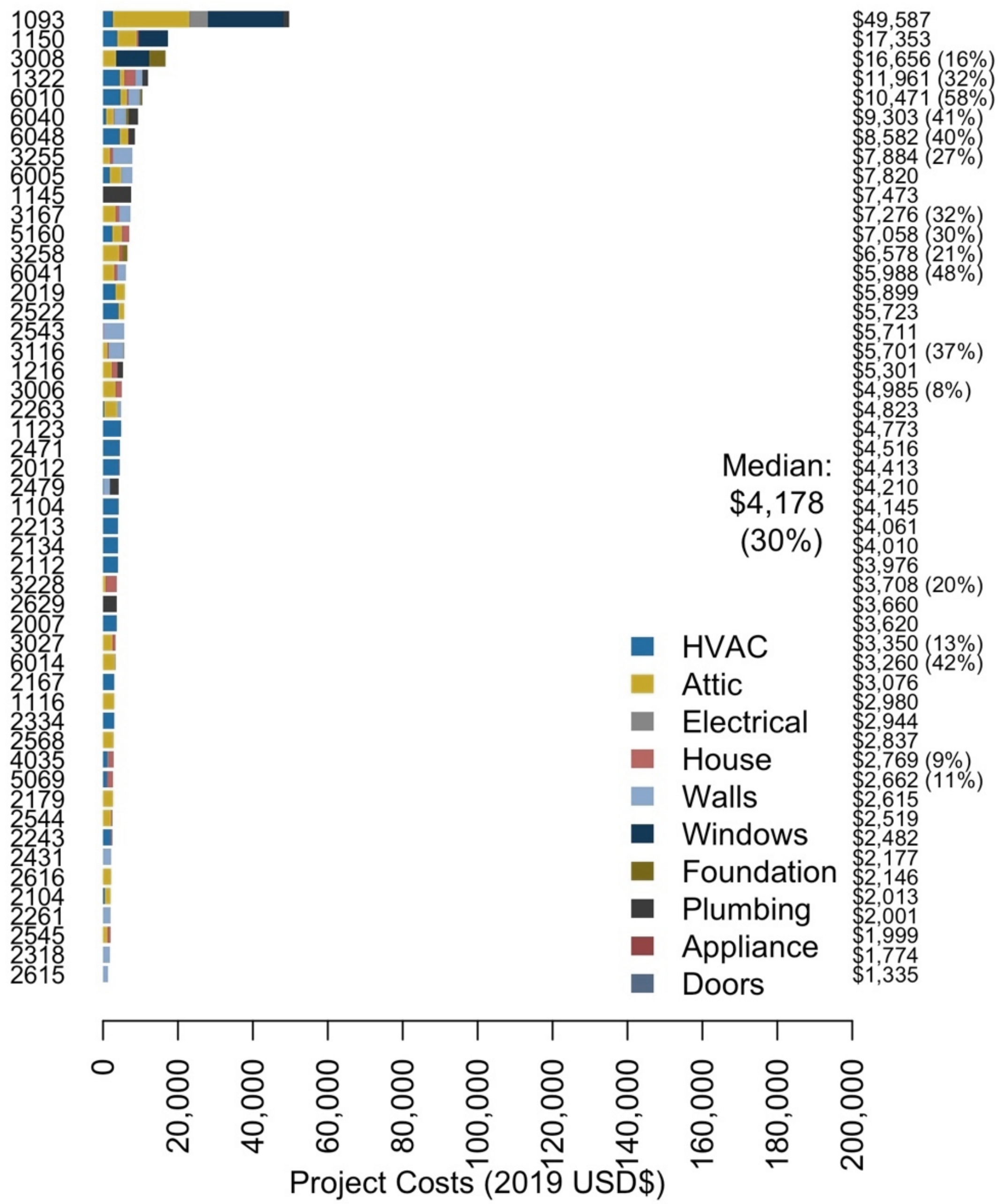


Figure D 2. Basic: Project Costs – Net-Site Energy

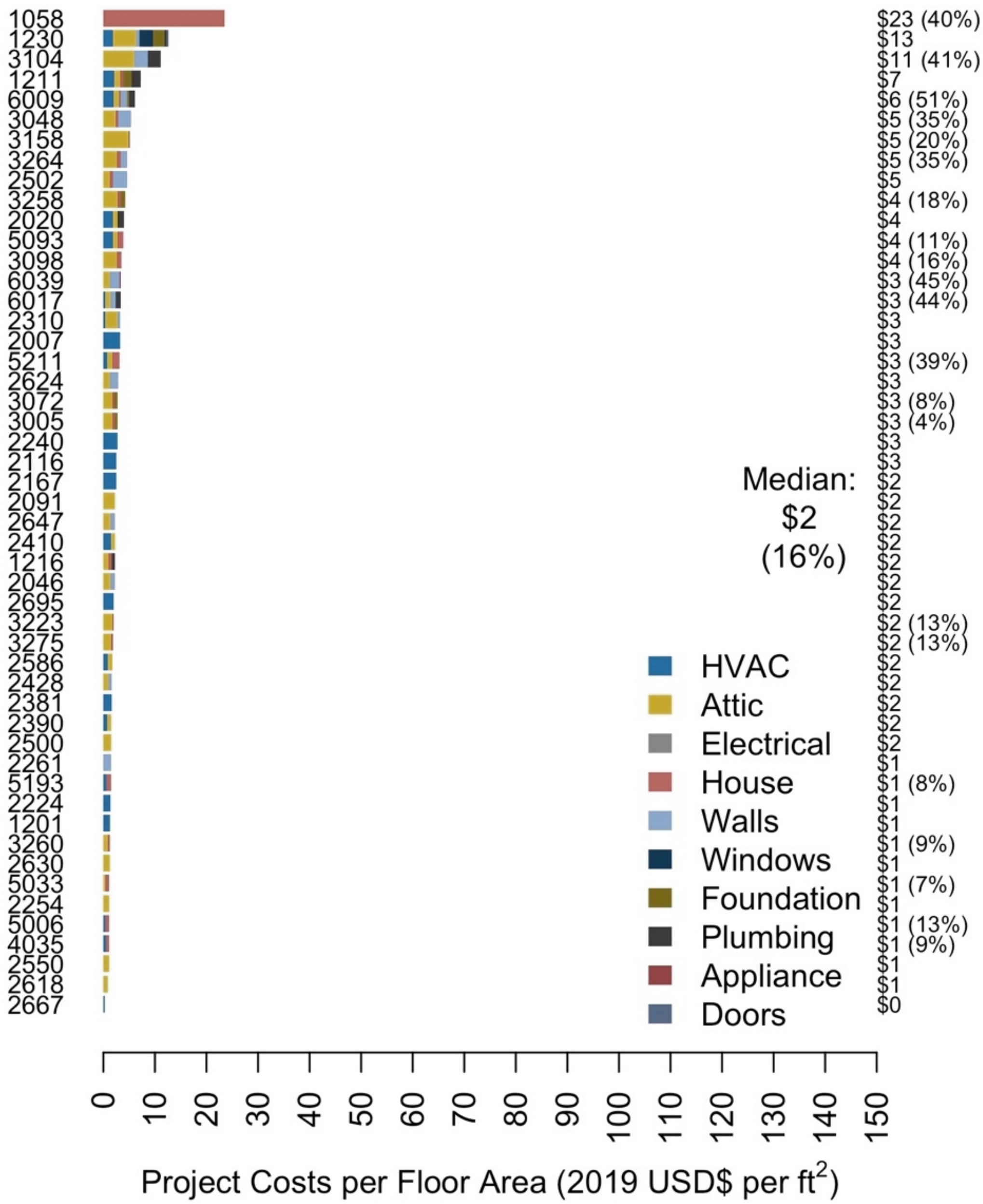


Figure D 3. Basic: Project Costs per Floor Area – Carbon

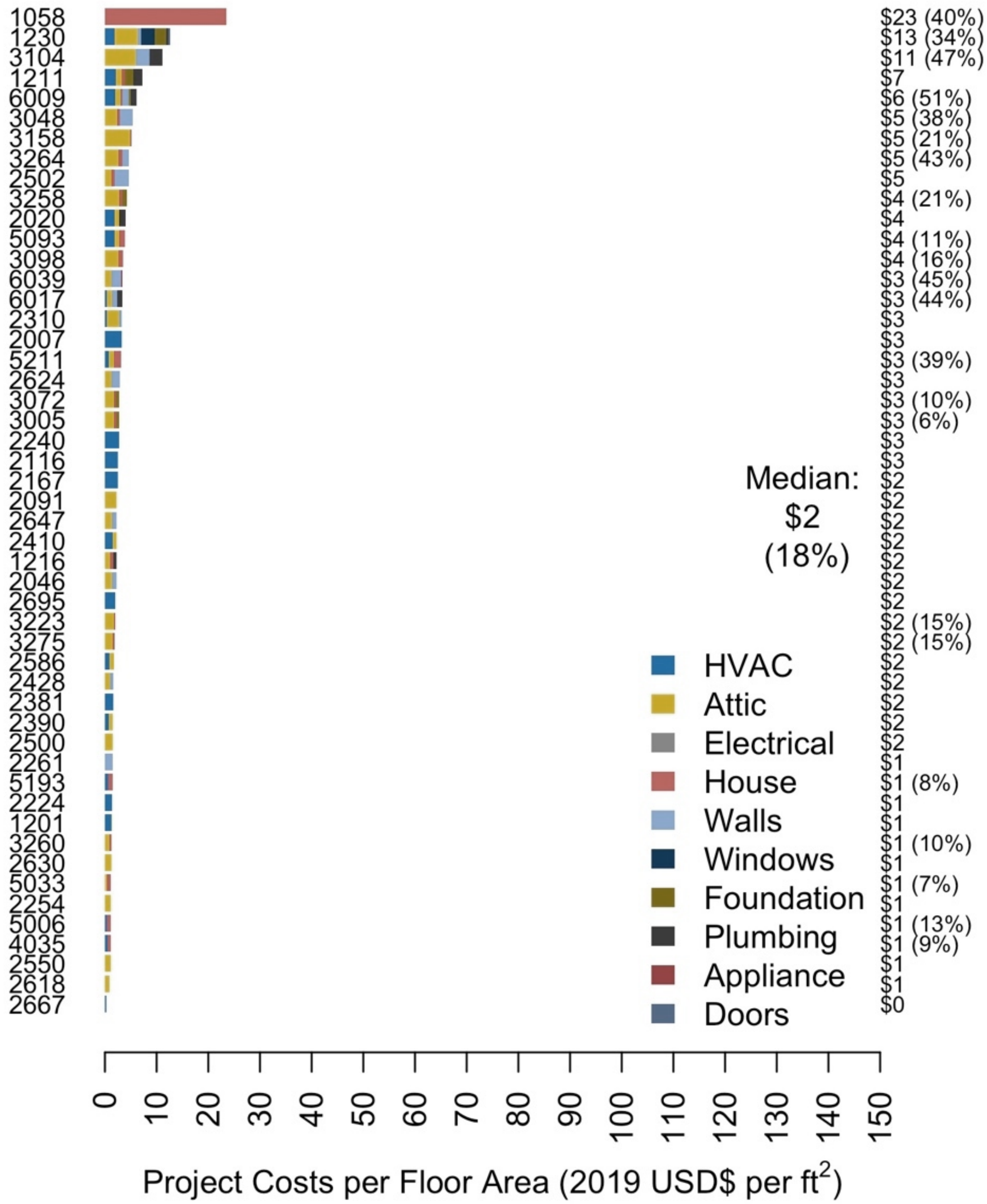


Figure D 4. Basic: Project Costs per Floor Area – Net-Site Energy

D.2 Medium-Cost Weatherization

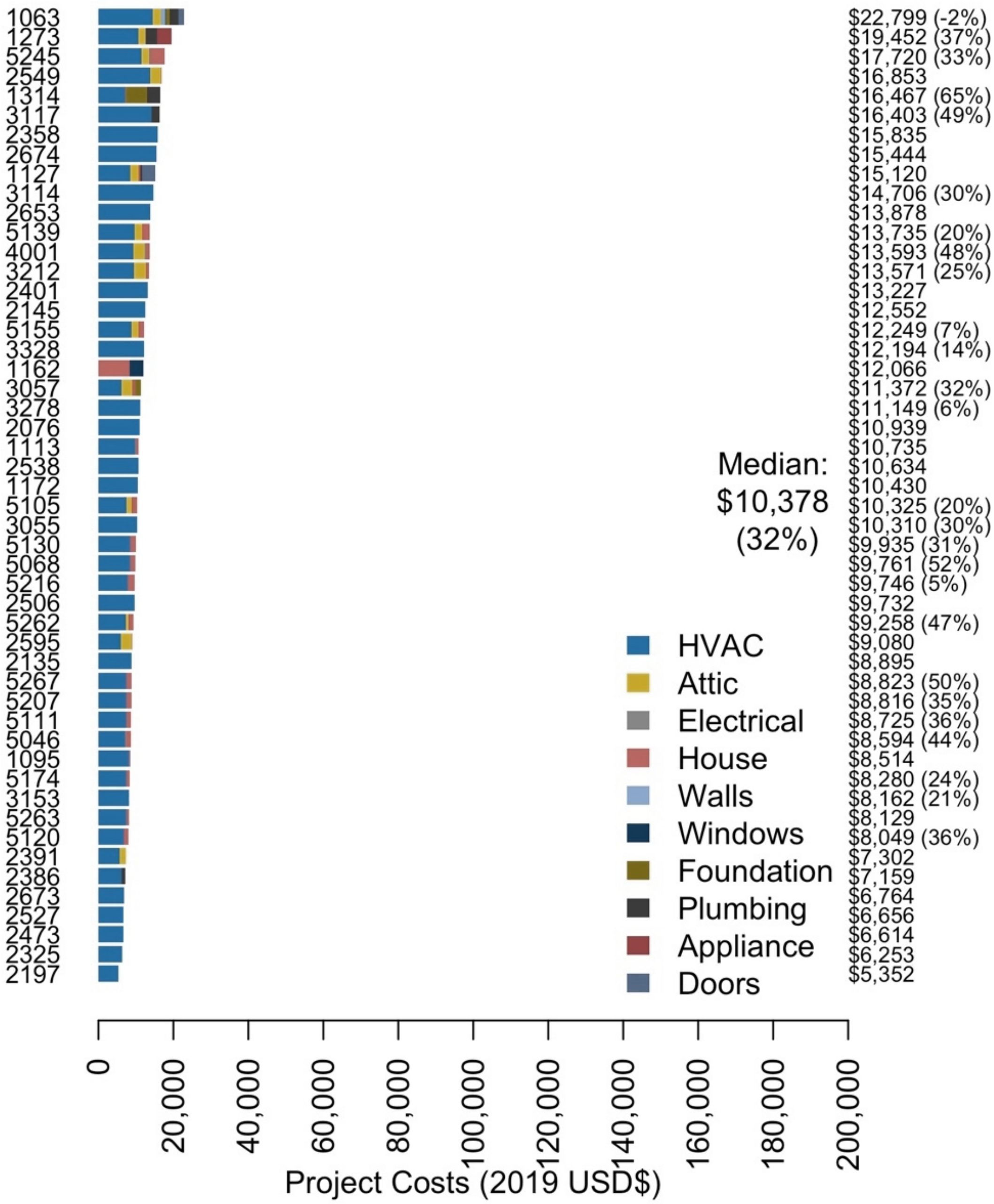


Figure D 5. HVAC: Project Costs - Carbon

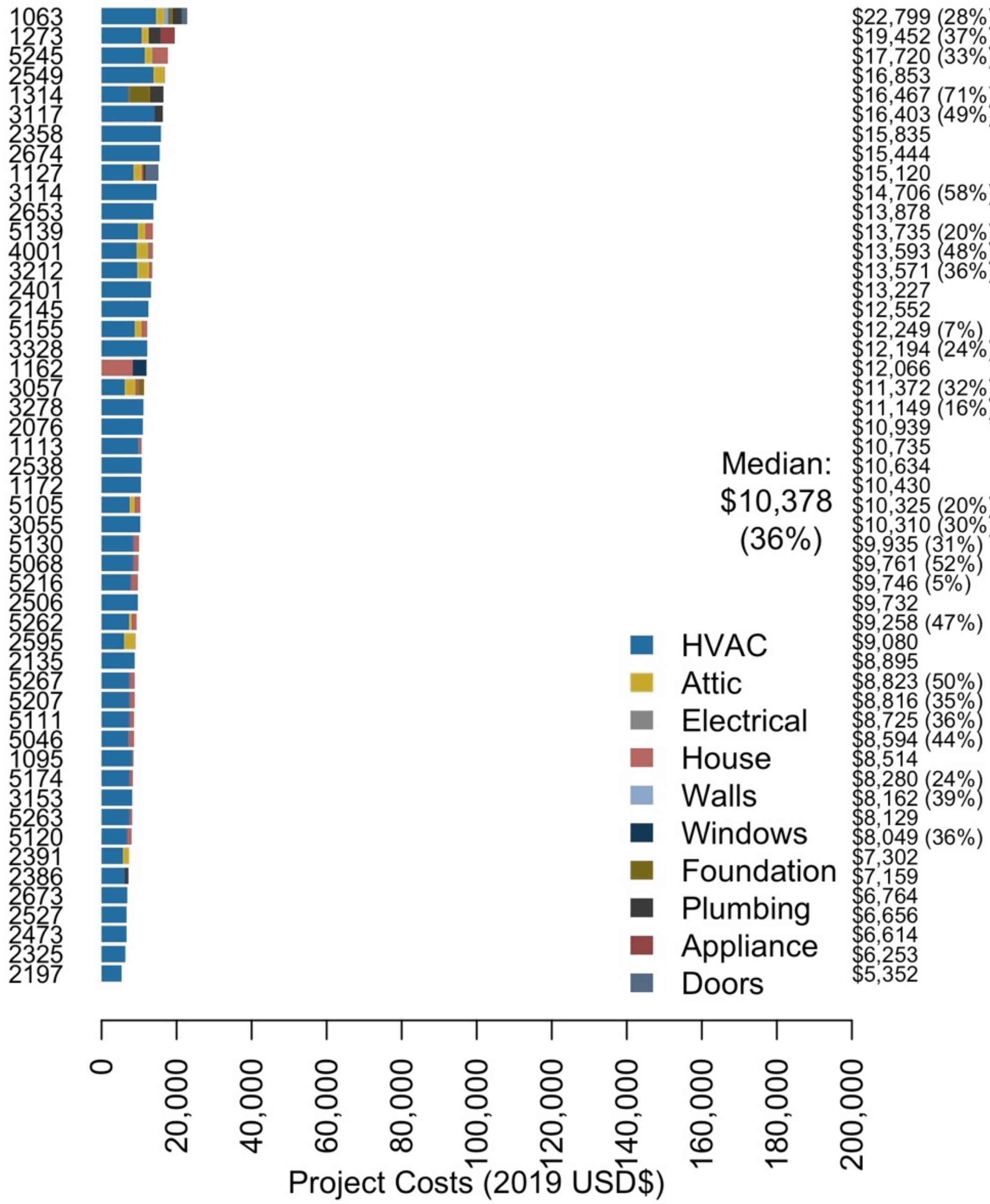


Figure D 6. HVAC: Project Costs – Net-Site Energy

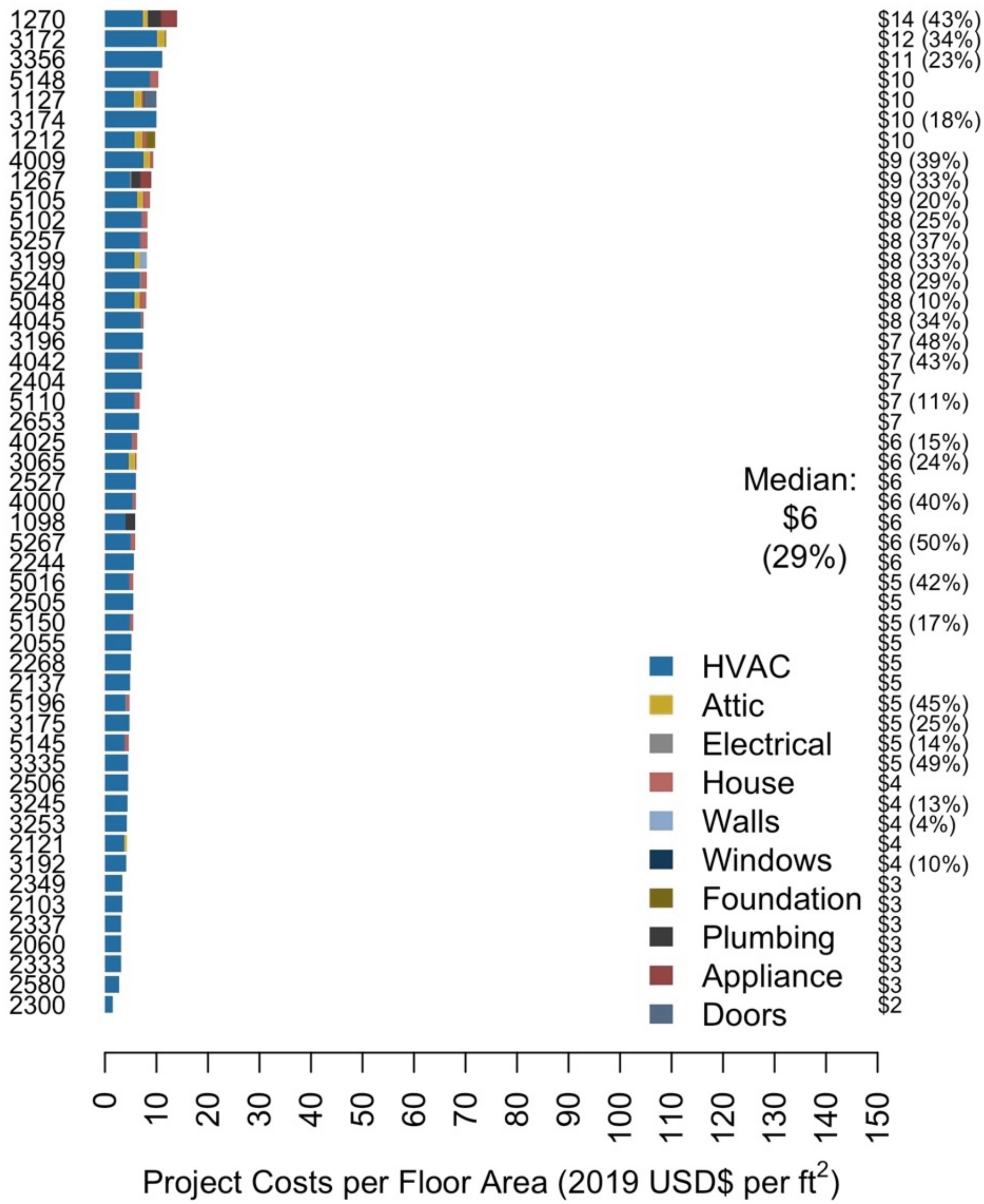


Figure D 7. HVAC: Project Costs per Floor Area – Carbon

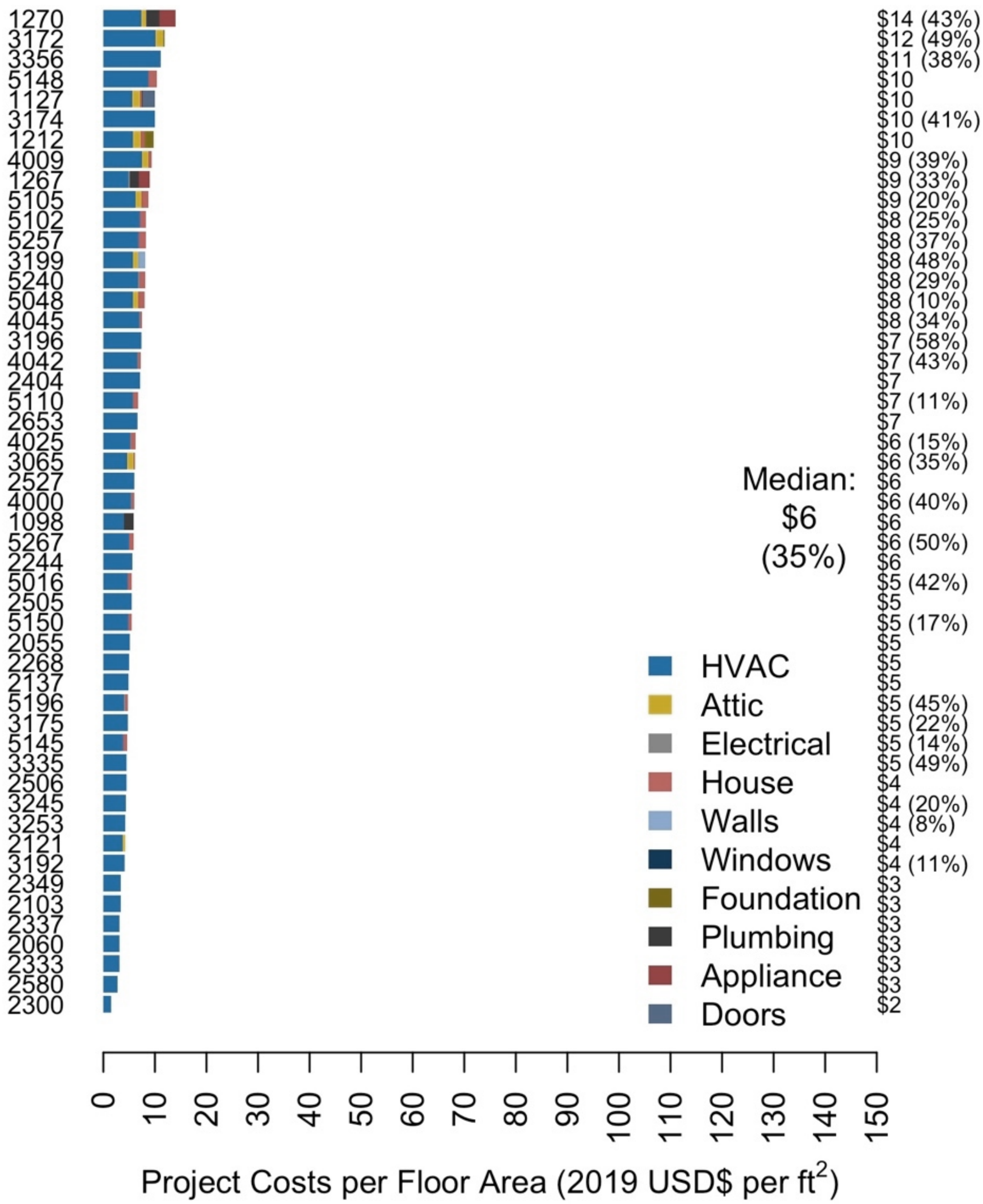


Figure D 8. HVAC: Project Costs per Floor Area – Net-Site Energy.

D.3 Advanced HVAC

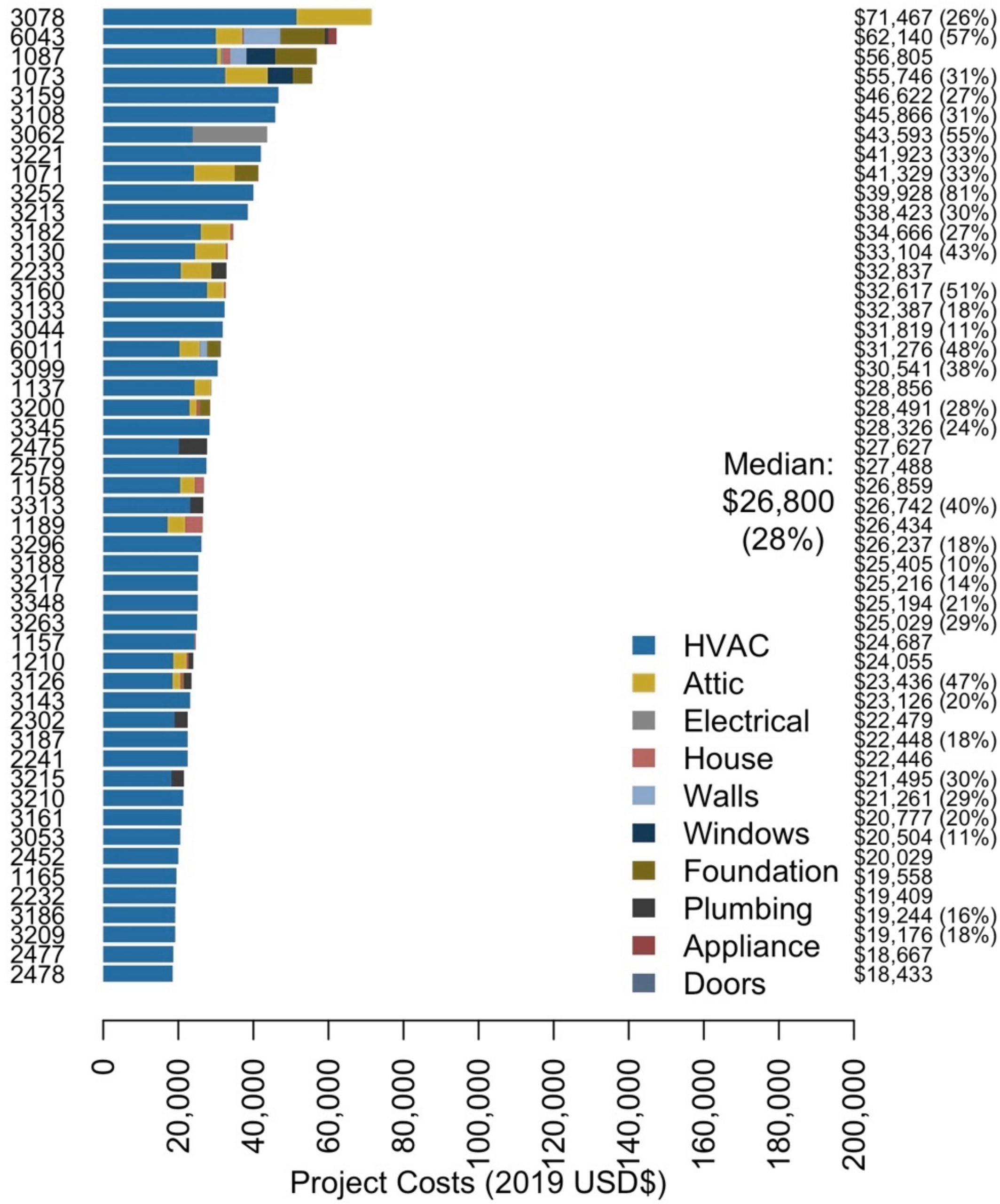


Figure D 9. Advanced HVAC: Project Costs– Carbon

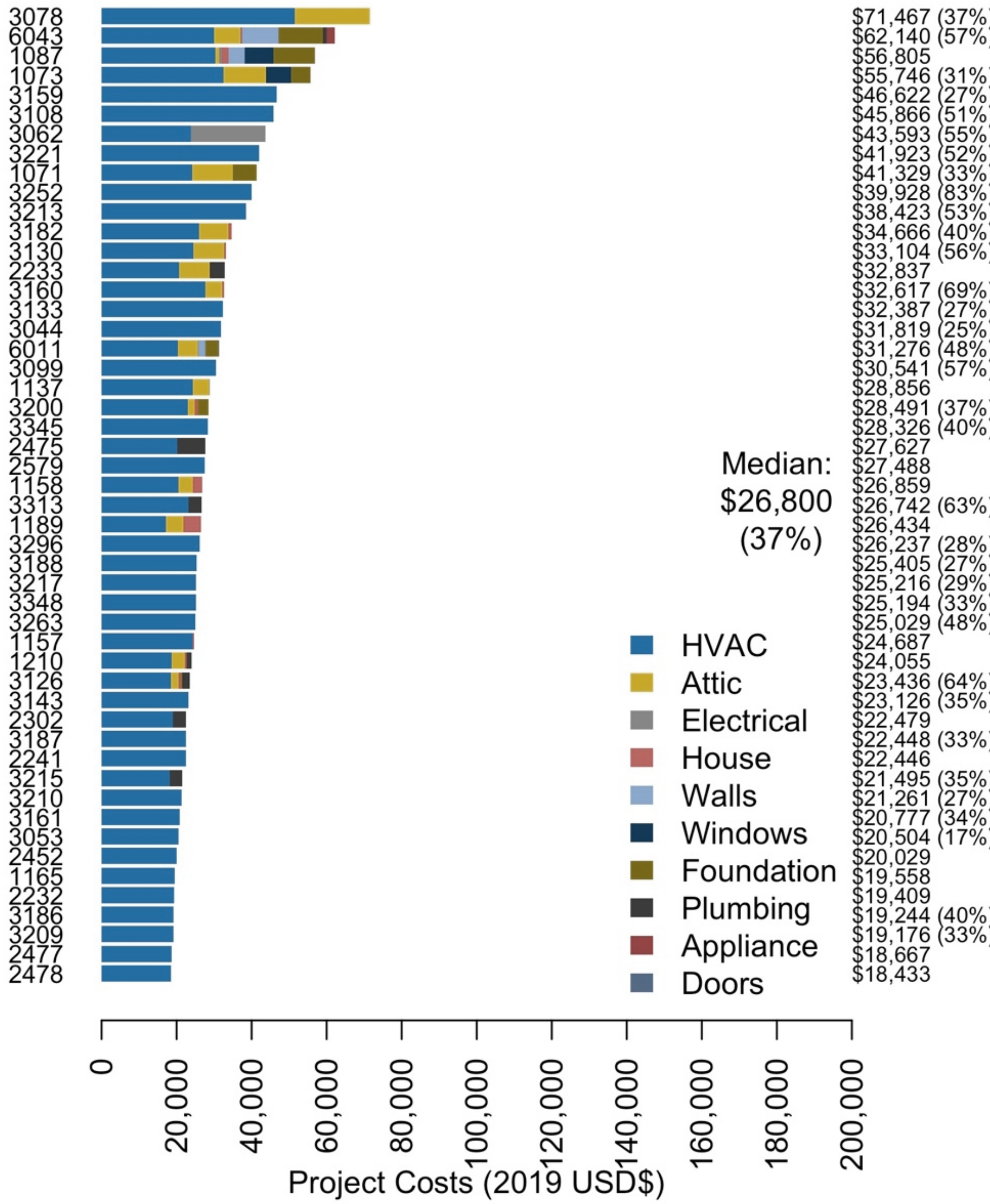


Figure D 10. Advanced HVAC: Project Costs – Net-Site Energy

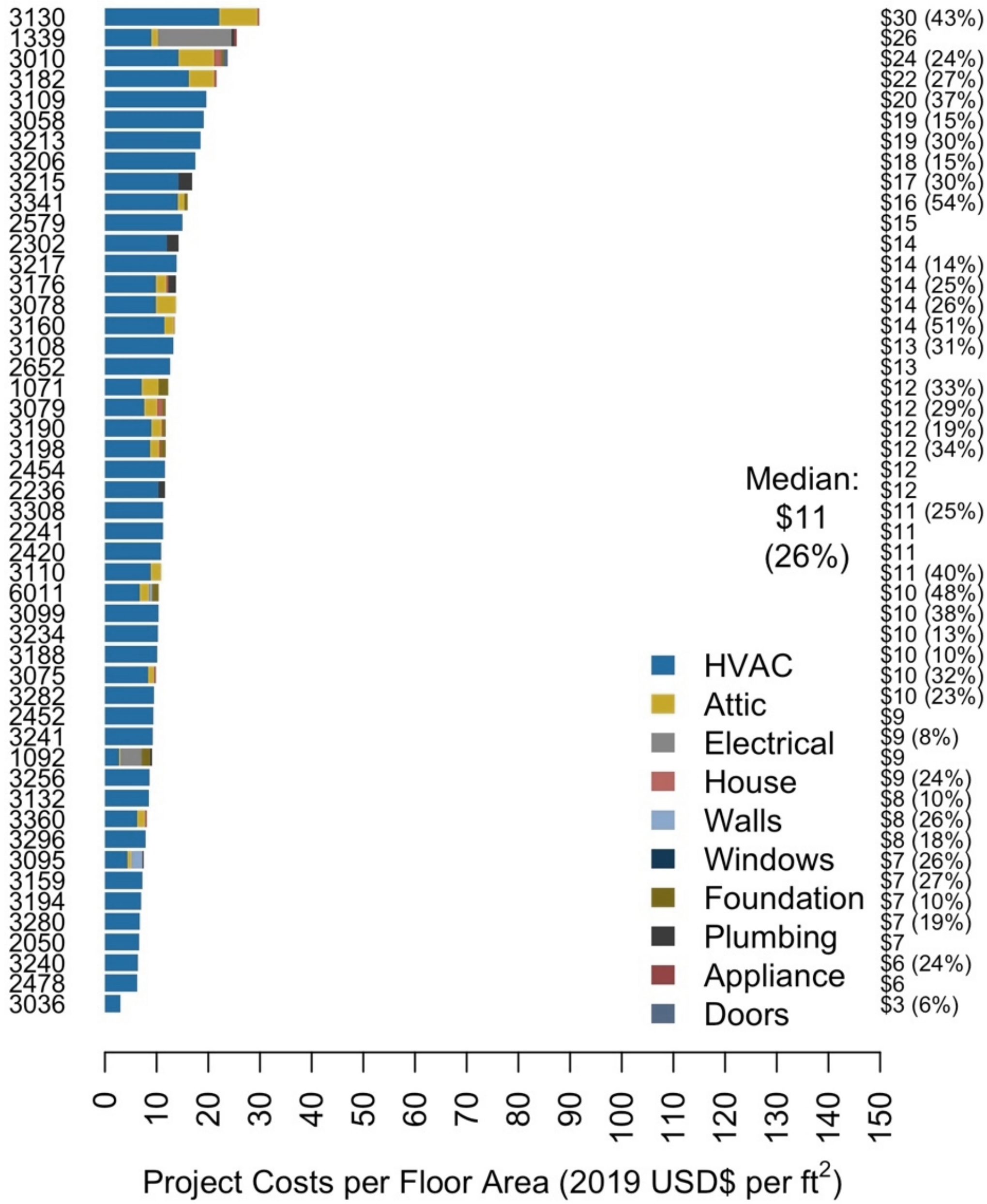


Figure D 11. Advanced HVAC: Project Costs per Floor Area – Carbon

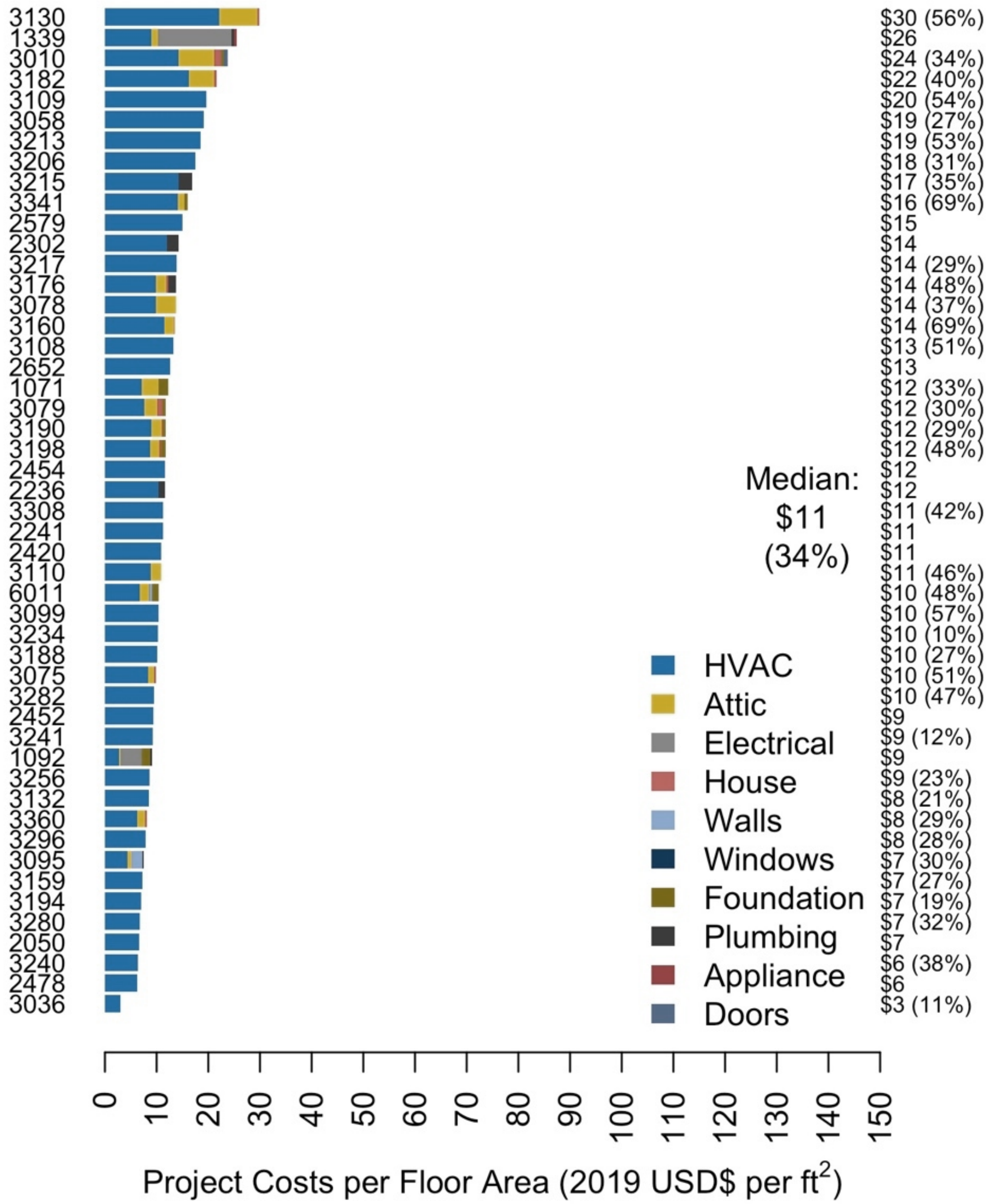


Figure D 12. Advanced HVAC: Project Costs per Floor Area – Net-Site Energy

D.4 Large Home Geothermal

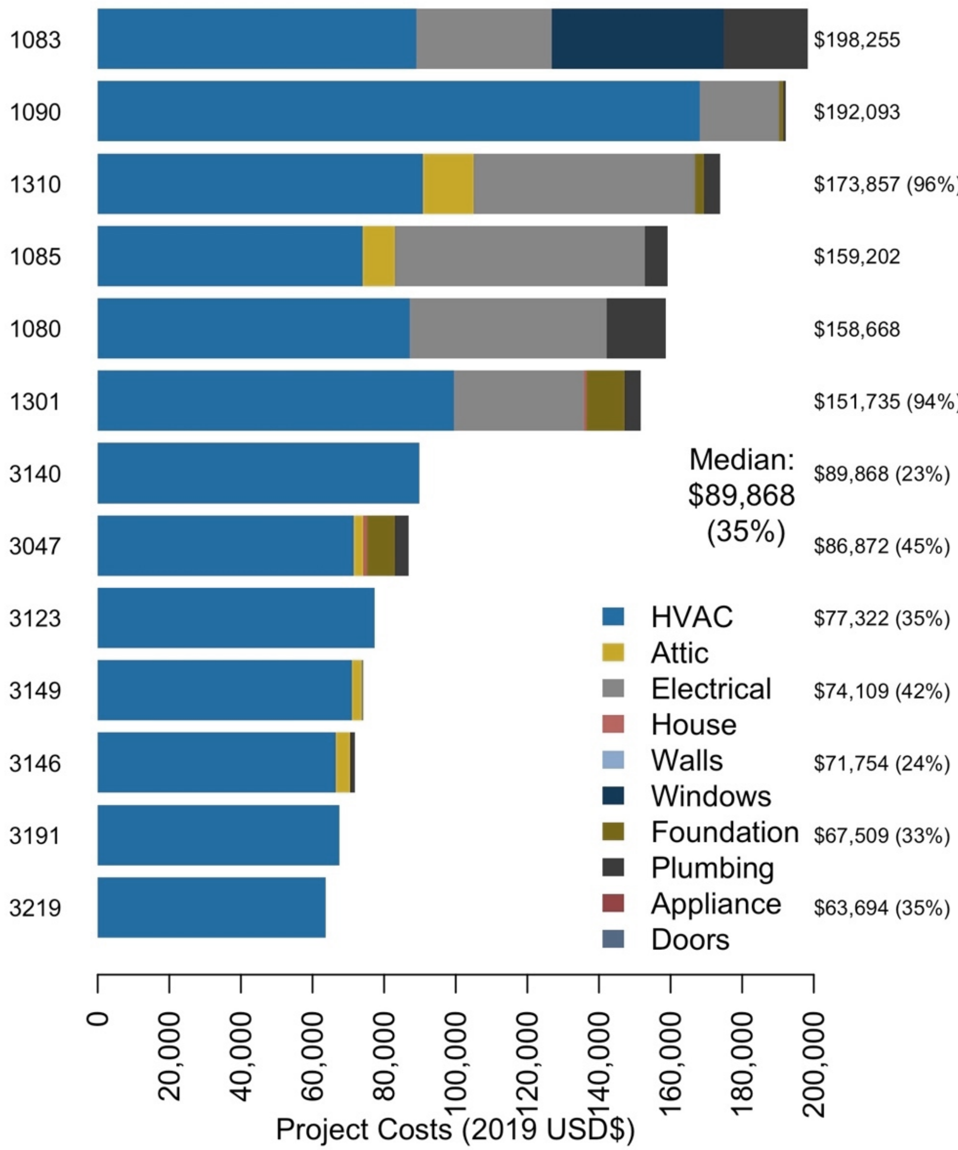


Figure D 13. High Cost HVAC Focused: Project Costs – Carbon

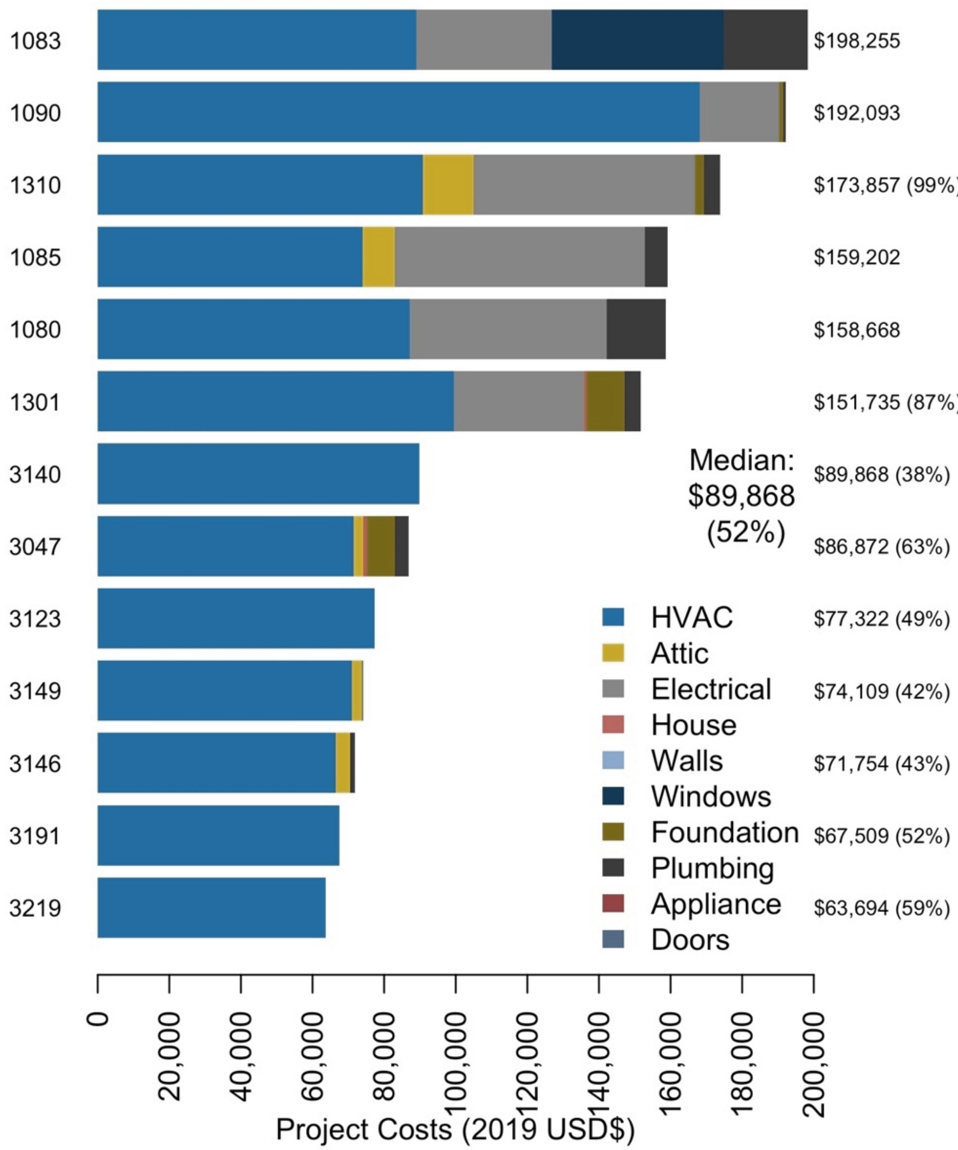


Figure D 14. High Cost HVAC Focused: Project Costs – Net-Site Energy

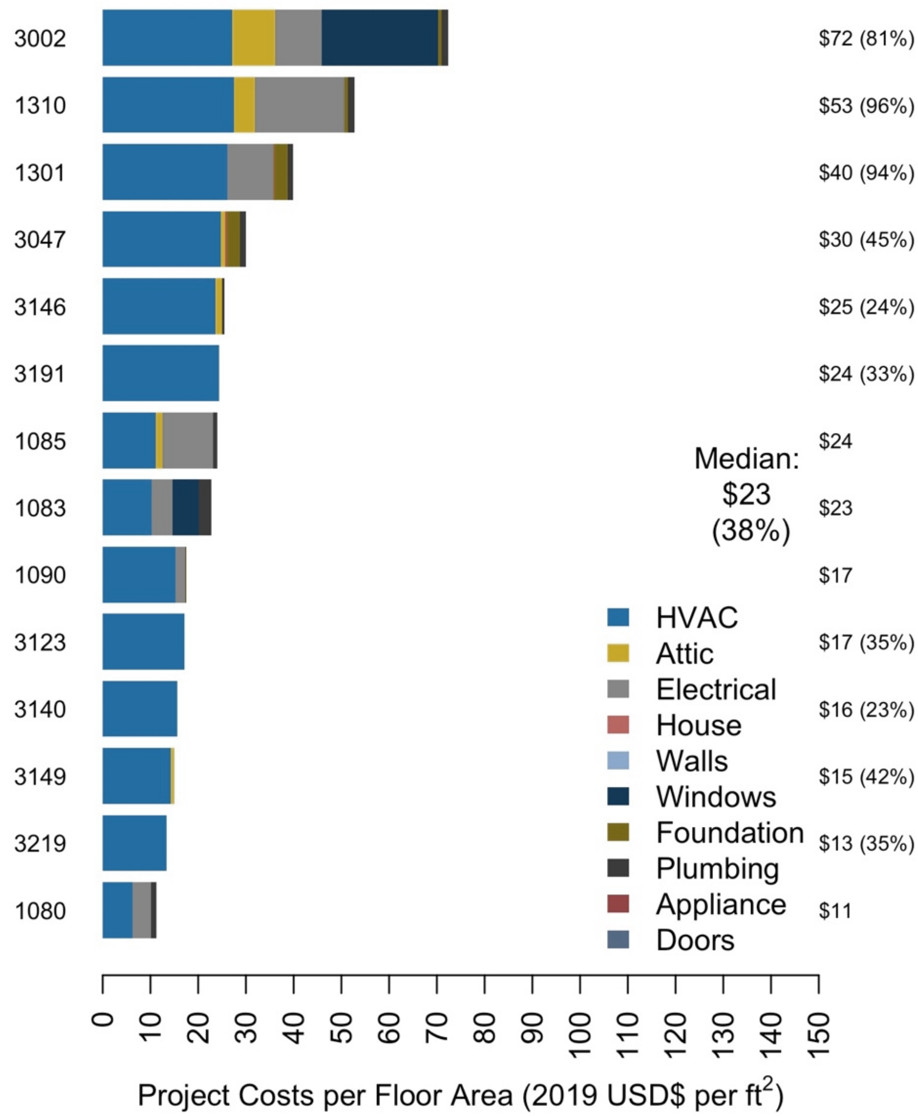


Figure D 15. High Cost HVAC Focused: Project Costs per Floor Area – Carbon

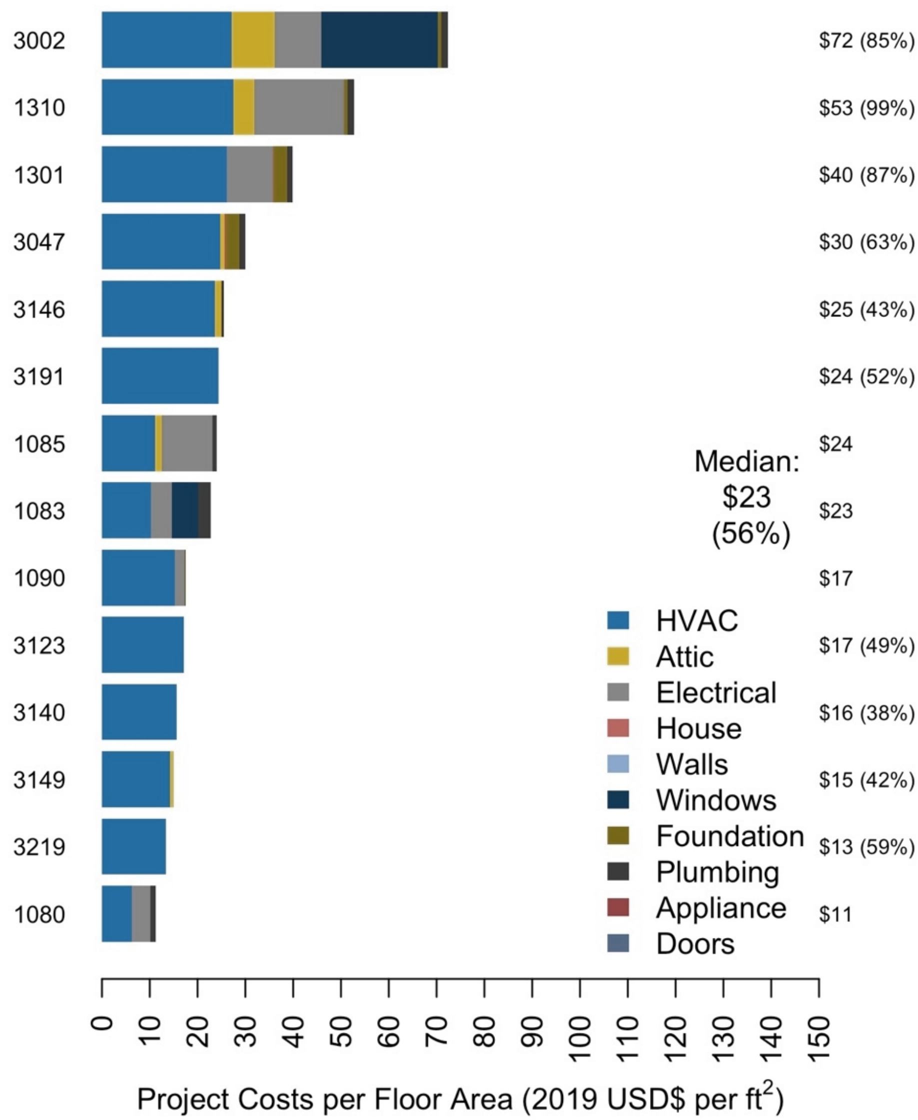


Figure D 16. High Cost HVAC Focused: Project Costs per Floor Area – Net-Site Energy

D.5 Superinsulation

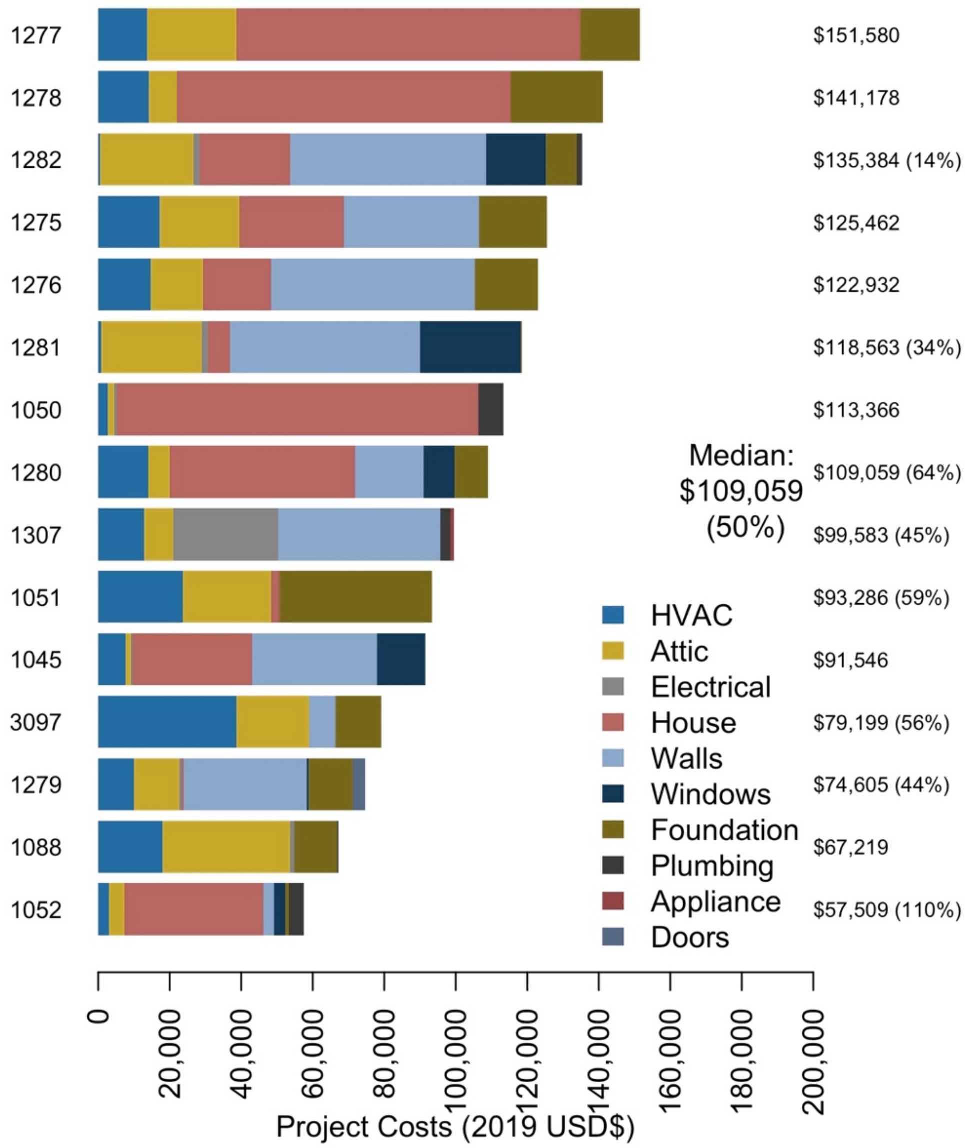


Figure D 17. Superinsulation: Project Costs – Carbon

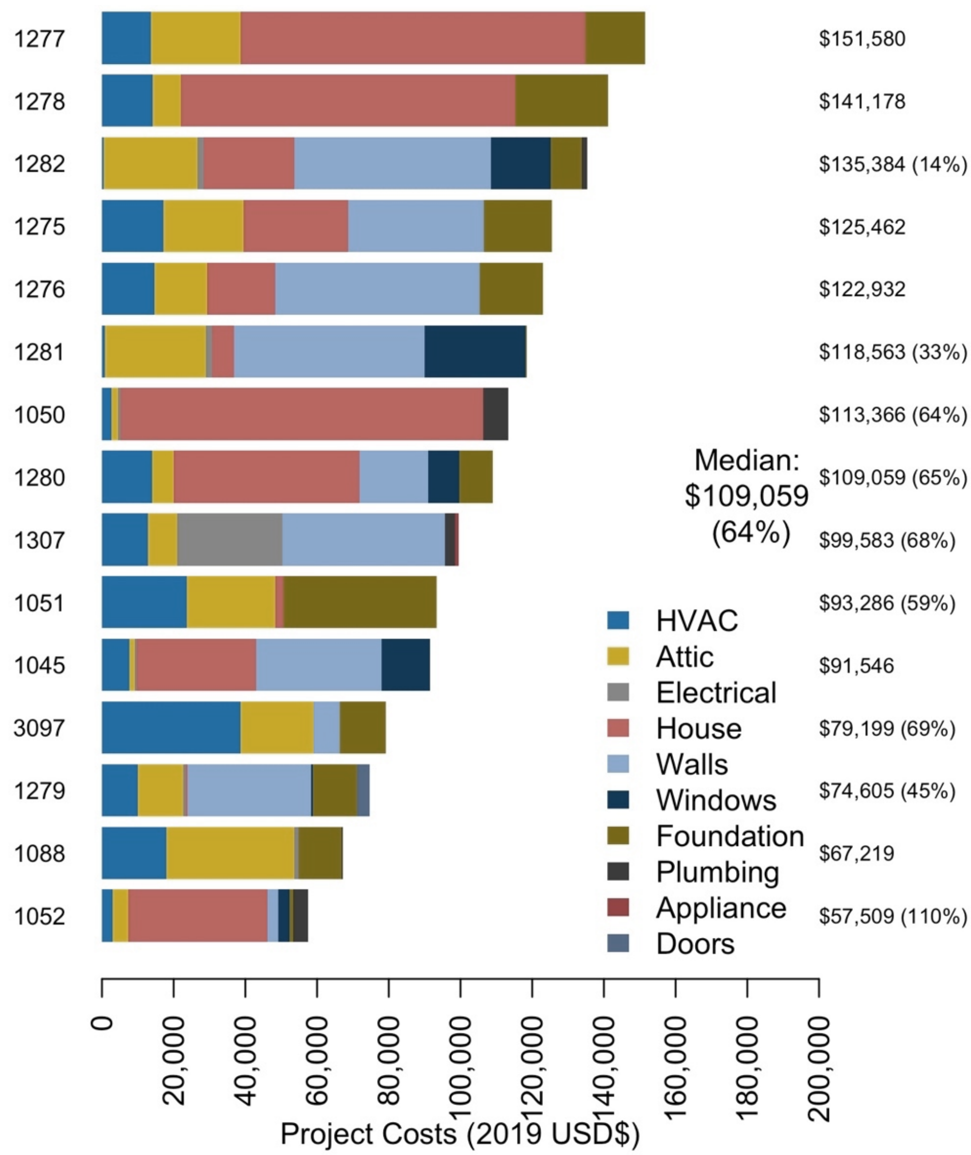


Figure D 18. Superinsulation: Project Costs – Net-Site Energy

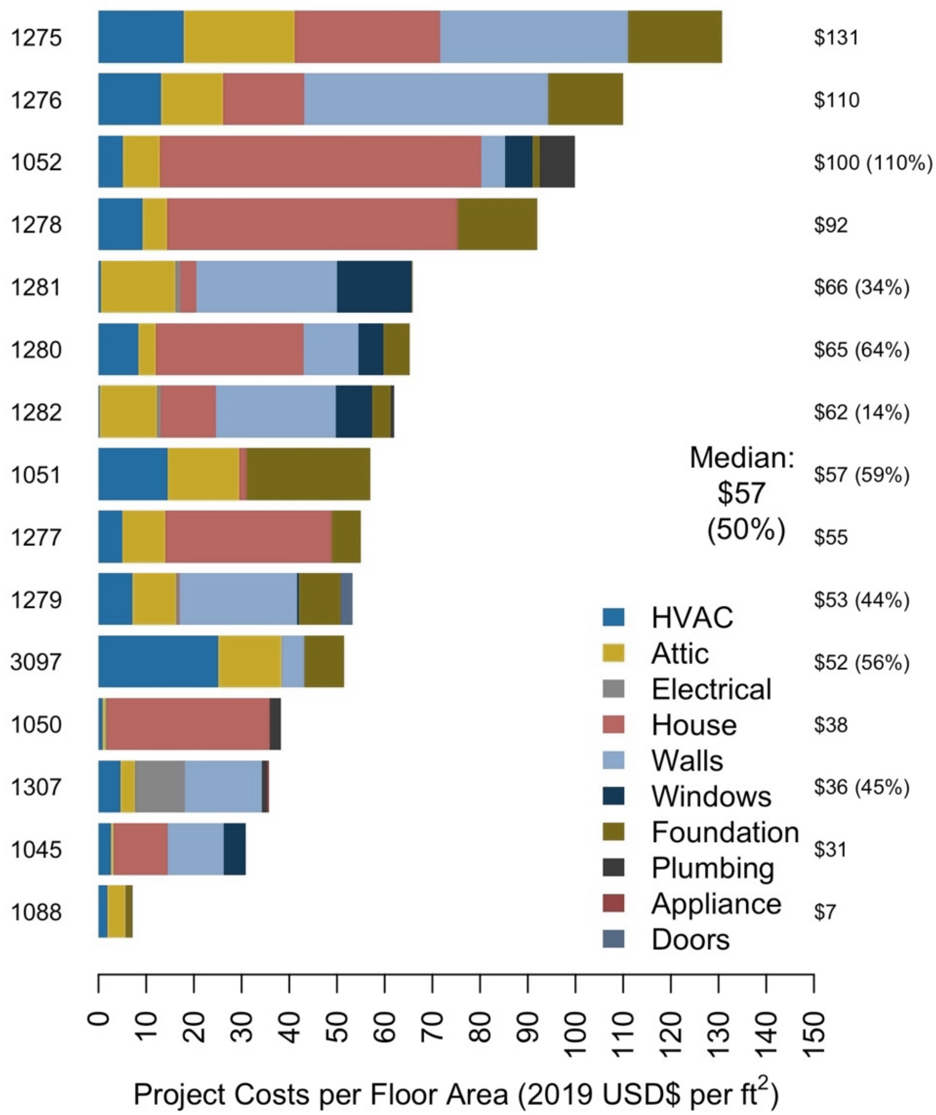


Figure D 19. Superinsulation: Project Costs per Floor Area – Carbon

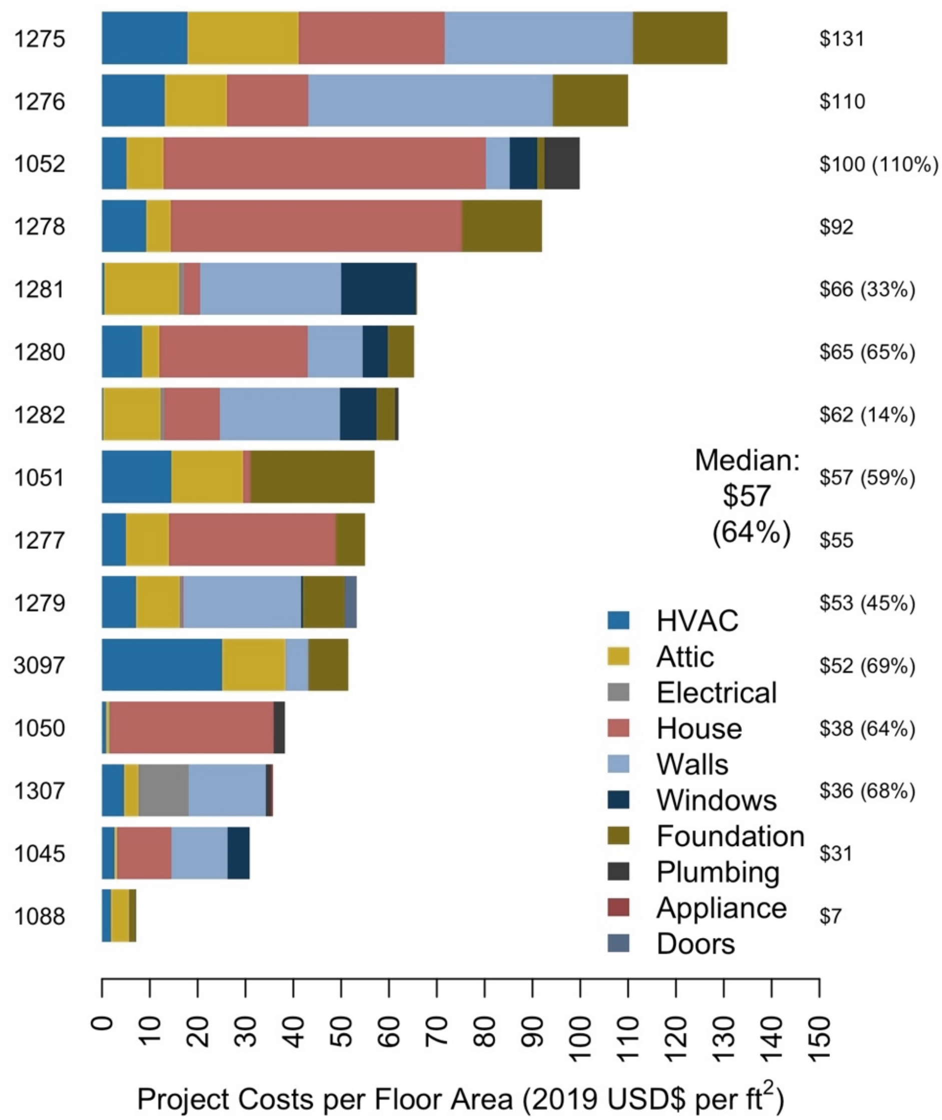


Figure D 20. Superinsulation: Project Costs per Floor Area – Net-Site Energy

D.6 Electrification with PV

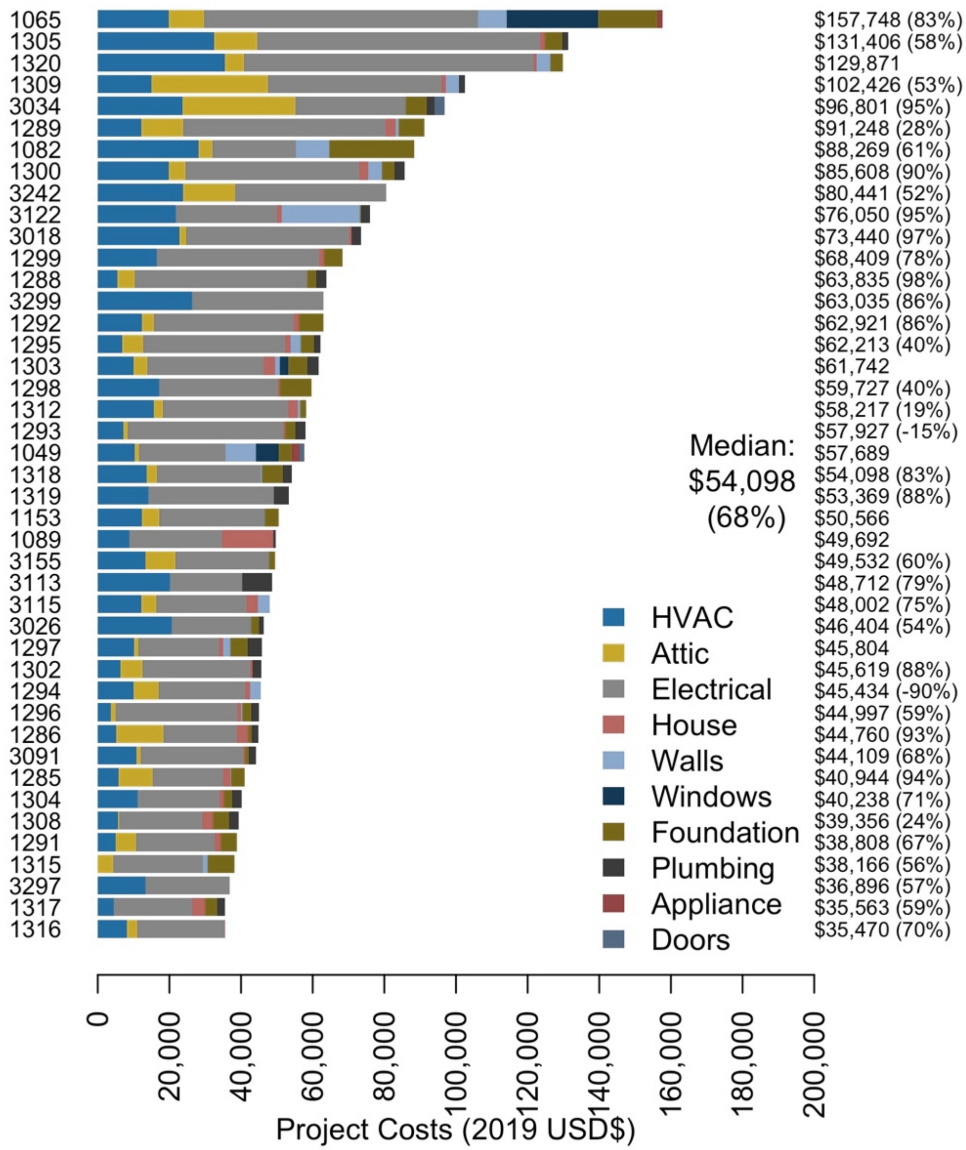


Figure D 21. Electrification with PV: Project Costs – Carbon

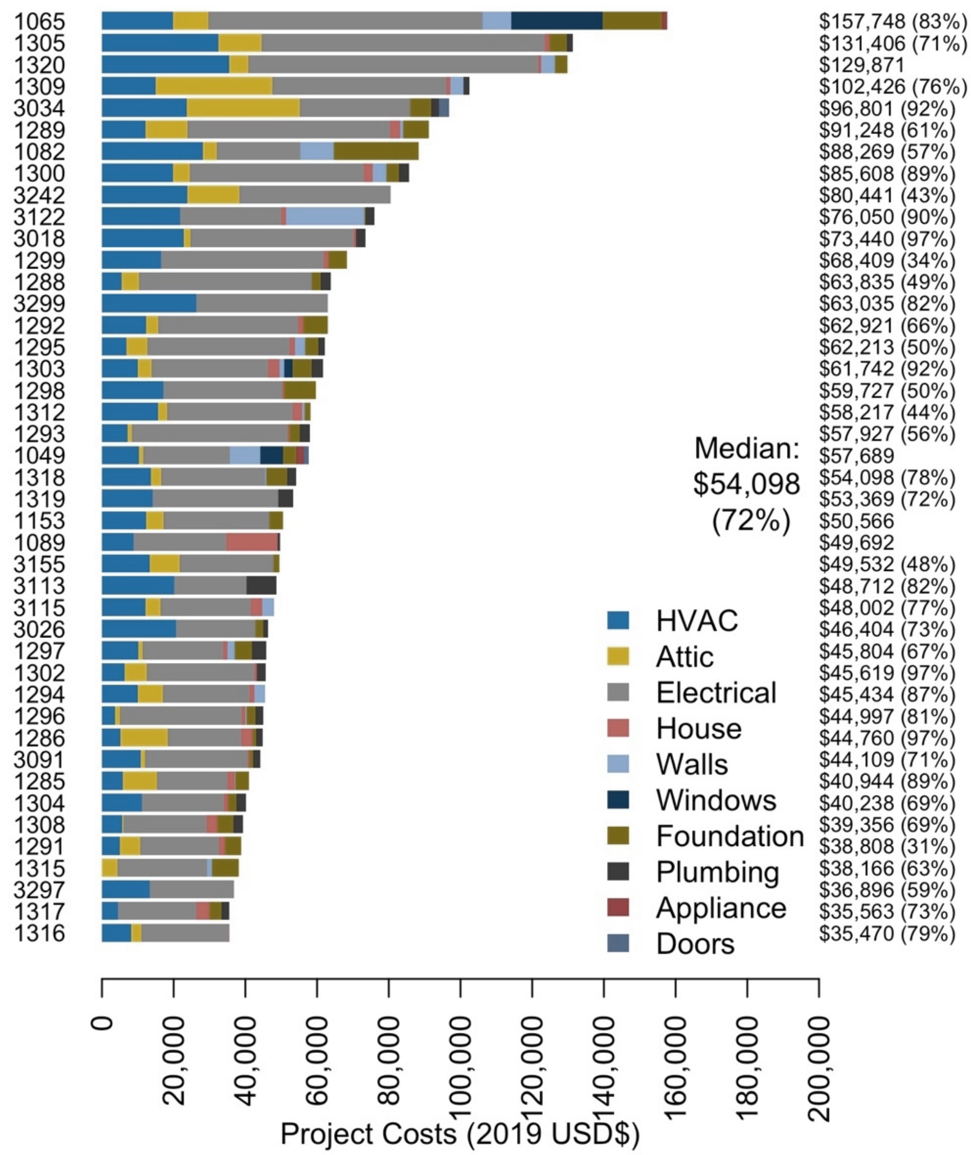


Figure D 22. Electrification with PV: Project Costs – Net-Site Energy

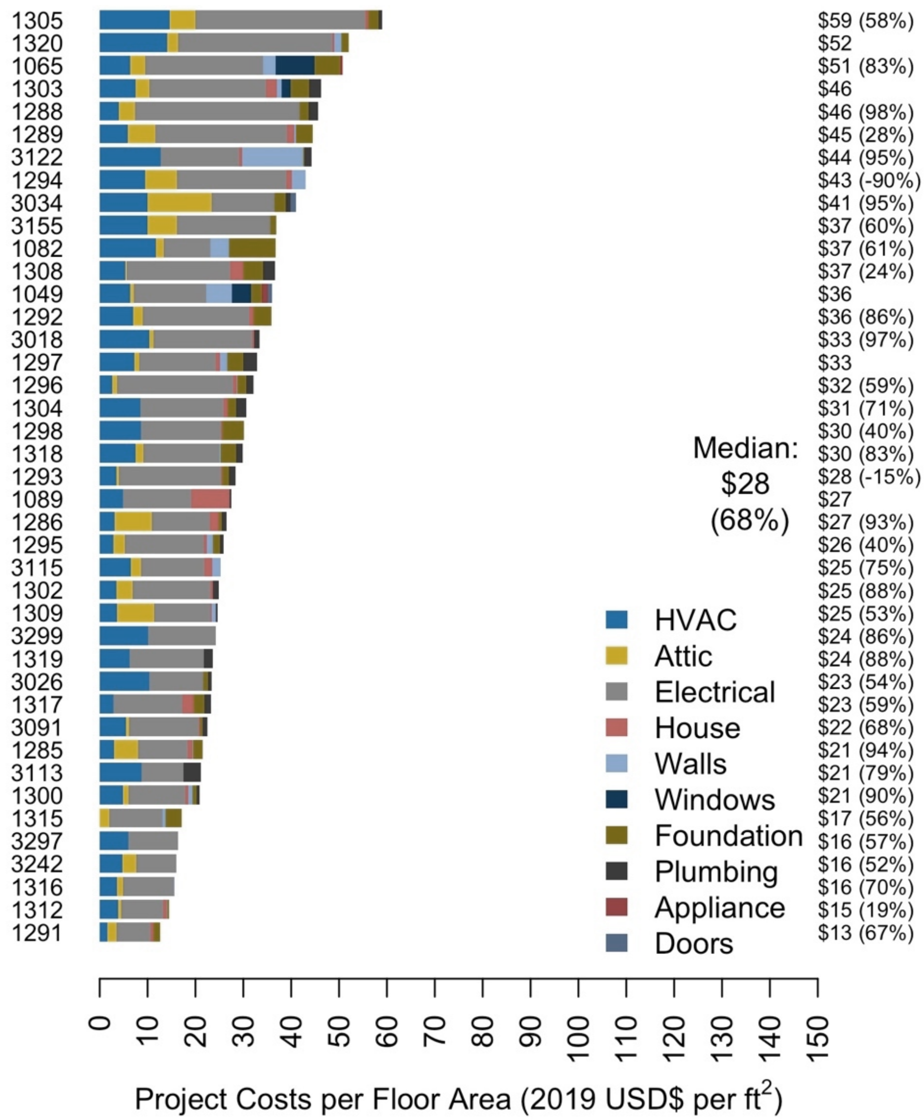


Figure D 23. Electrification with PV: Project Costs per Floor Area – Carbon

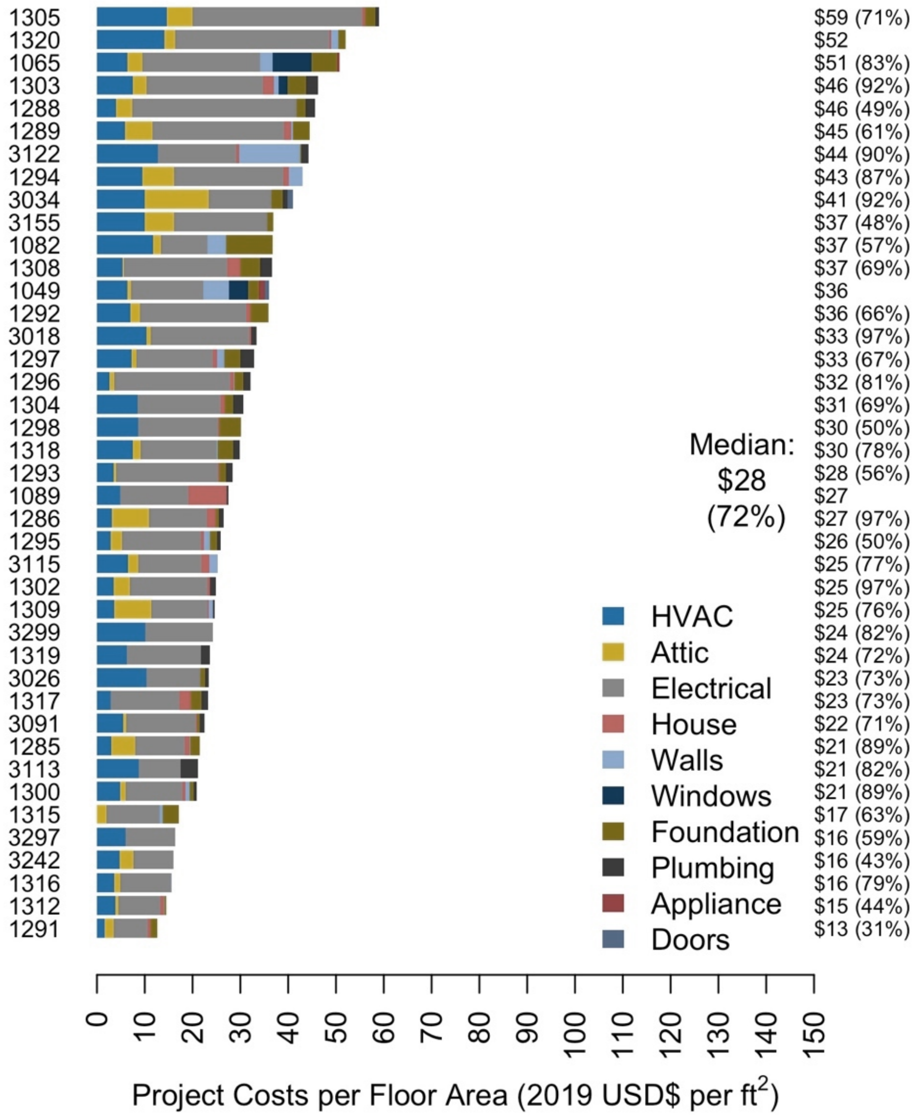


Figure D 24. Electrification with PV: Project Costs per Floor Area – Net-Site Energy.

APPENDIX E – Project Characterization

This report includes data gathered from 15 of the 50 states in the US, giving a total of 1,739 projects. 76.7% of the projects are single-family detached buildings, followed by manufactured homes (16.4%), and single-family attached buildings (4.3%). Only 1.8% of the data belongs to multi-family buildings. Table 14 summarizes the project characteristics. Many projects did not report some or all of these characteristics, so they do not always add up to the total number of projects.

The median conditioned floor area is 1,768 ft^2 (mean of 1,989 ft^2; n=1,657). The distribution of conditioned floor area is shown in Figure E1. Only six projects in the entire database recorded a change in the conditioned floor area from pre- to post-retrofit, suggesting that most projects were not major remodels/additions, where these changes are more common. Of those six, four projects reported small reductions in floor area, while the other two projects reported increases to floor area. Overall, we conclude that changes in floor area are uncommon in current energy upgrade work in the US.

Projects in the database occurred from 2010-2020, but the projects are concentrated in the most three recent years—2020 (n=828), 2019 (n=374) and 2018 (n=258). This should not be interpreted as a signal that whole home upgrades are becoming more prevalent generally. Much of this is determined by the operation years of programs that contributed data, such as CA MTC - BayREN Home+, MA DOER - Home MVP, and TN/NC - EEtility PAYS (see Section 7.4 for a discussion of programs). Yet, the number of projects in 2020 is notable, especially during the global COVID-19 pandemic.

The distributions of project costs and incentives are described in detail in Section 4.1, and all of the project characterization metrics (e.g., cost, incentives, floor area) are summarized in subsections below according to Climate Zone (Section 7.2), retrofit type (Section 7.3), energy program participation (Section 7.4).

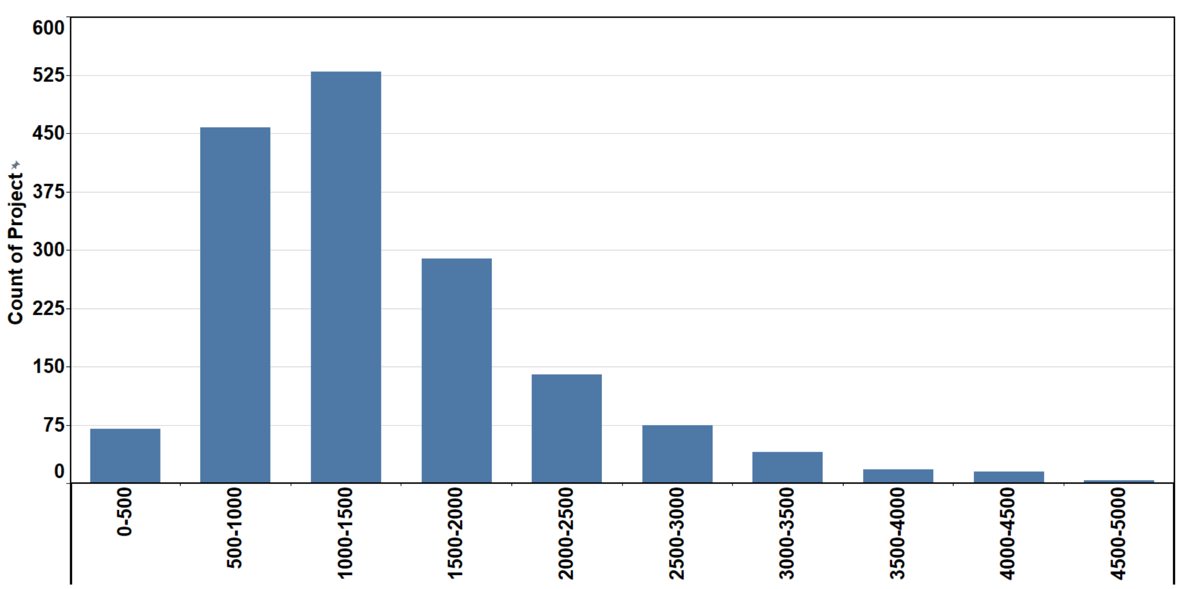


Figure E 1. Conditioned Floor Area (CFA) per project (ft^2) [project ranked from lowest to highest CFA.]

E.1 Project Costs and Incentives

All project costs in this report are adjusted to represent 2019 US dollars ($) and are adjusted to be representative of national average costs. The distribution of floor area normalized project costs is shown in Figure E 2. When filtering to include only projects with three or more measures, the floor area normalized costs increase to a median of $6.27/ft^2 (mean of $9.28/ft^2; n=880). The 95th percentile floor area normalized project cost is $23.80/ft^2.

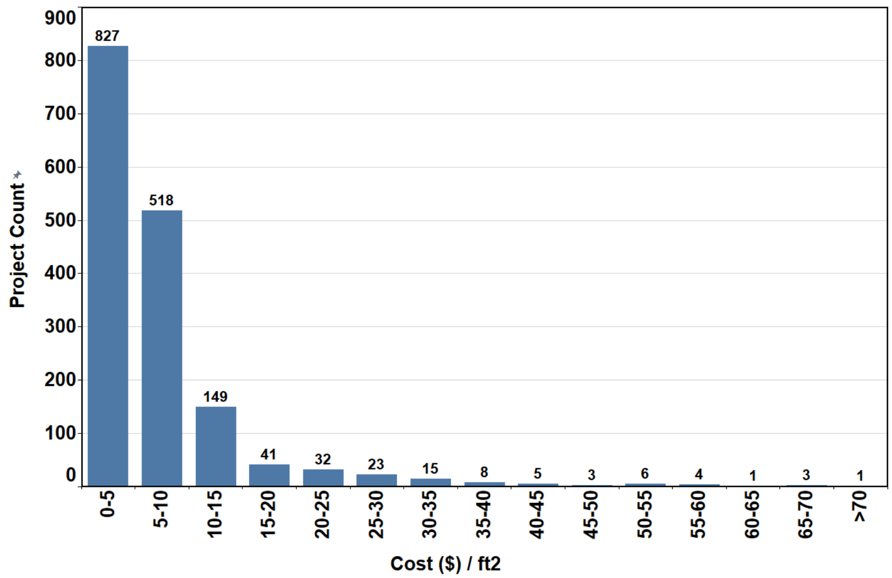


Figure E 2. Project cost ($/ft^2) [project ranked from lowest to highest $/ft^2.]

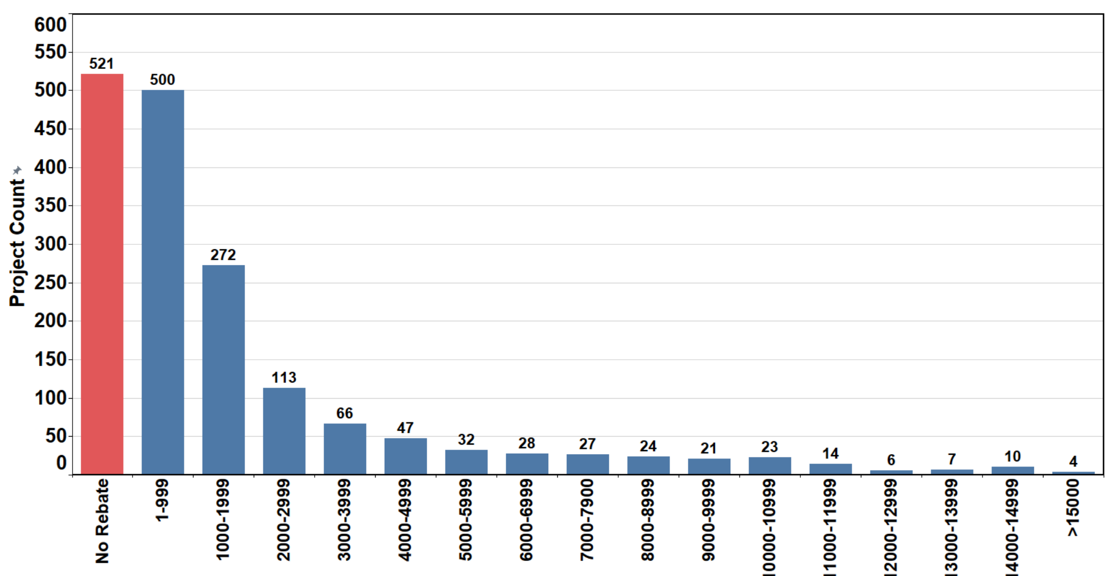


Figure E 3. Distribution of retrofit incentive per project ($).

Rebate measures were the most frequently recorded actions in the database. These represent rebates recorded as individual measures in the database (e.g., three line-item rebates for HVAC, wall insulation and for attic insulation in a single dwelling), and the median measure-level rebate was $559 (mean value of $1,765). Many projects included more than one rebate measure, and when added up at the project level, the median total Rebate was $1,327 (mean of $3,053). These project-level rebate values are summarized in a histogram in Figure E 3. 71% of projects (1,218) reported some rebates, with a total of 2,108 rebate measures recorded in total. Rebates were highly variable by program participation, with some programs heavily incentivizing retrofit work and others not at all. At the whole-project level, for those projects reporting rebates, they accounted for a median of 21% of the total project costs (mean of 30%). The fraction of total project costs that were rebated are shown in Figure E 4. Notably, a small subset of projects reported incentives that were equal to 100% of the gross project costs.

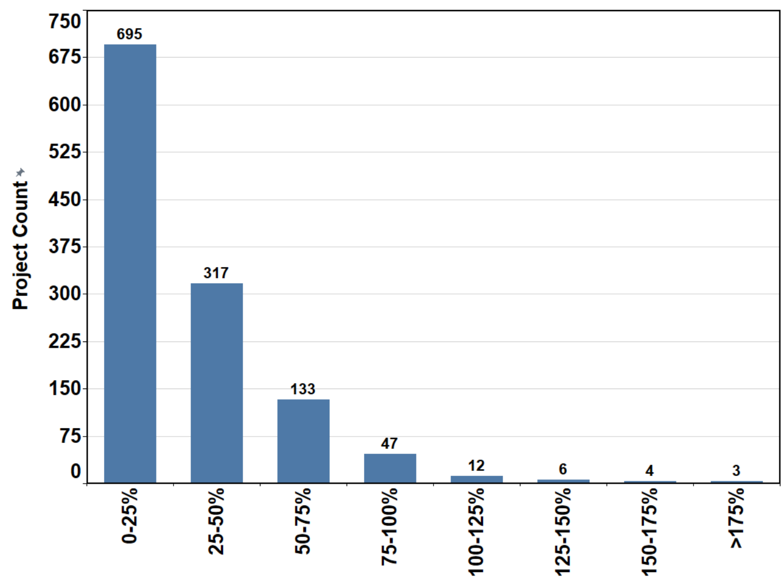


Figure E 4. Distribution of retrofit incentive fraction (%).

E.2 Climate Zone

The count of projects in each US DOE climate zone (CZ) is shown in Table E 1, and we see that the most projects were recorded in CZ 3C, 4A, 5A, and 3B. Much smaller but still substantial numbers of projects were recorded in CZ 6A and in 2A. Consistent with this, the state with the most projects recorded in the database is CA with a total of 847 (CZ 3B and C), followed by MA with a total of 366 (CZ 5A). The project metrics of floor area, gross project costs, incentives and incentive fraction are also summarized by climate zone in Table E 1.

Table E 1. Climate zone summary per number of projects.

CLIMATE ZONE	Number of Projects	Median Conditioned Floor Area (ft^2)	Median Gross Project Cost ($/$ft^2$)	Median Gross Project Cost ($)	Median Project Incentive ($)	Median Incentive Fraction (%)
2A	60	1,304 (n=60)	$14 (n=60)	$20,117 (n=60)	---	---
3A	17	3,829 (n=16)	$15.27 (n=16)	$56,805 (n=17)	---	---
3B	**248**	**1,833 (n=184)**	**$2.96 (n=181)**	**$7,503 (n=245)**	**$941 (n=213)**	**13.9% (n=213)**
3C	**594**	**1,736 (n=583)**	**$2.96 (n=570)**	**$5,487 (n=581)**	**$852 (n=552)**	**14.4% (n=552)**
4A	**331**	**1,600 (n=331)**	**$5.62 (n=331)**	**$9,286 (n=331)**	**---**	**---**
4B	2	1,778 (n=2)	$19.25 (n=2)	$31,231 (n=2)	---	---
5A	**369**	**2,080 (n=369)**	**$7 (n=369)**	**$13,655 (n=369)**	**$5,045 (n=361)**	**37.4% (n=361)**
5B	1	872 (n=1)	$31.12 (n=1)	$27,139 (n=1)	$1.596 (n=1)	5.9% (n=1)
6A	92	2,093 (n=90)	$7.28 (n=90)	$16,695 (n=92)	$1,682 (n=84)	16.21% (n=84)
No Response	25	(n=103)	(n=119)	(n=41)	(n=528)	(n=528)

E.3 Retrofit Type

Each project was categorized during data entry for its retrofit type, and the count of projects in each type is shown in Table E 2.

This feature is necessarily subjective but was intended to capture project strategies at a high-level, such as Electrification or envelope-focused. Retrofit types with more than 100 projects are in bold font. Once again, median floor area is higher in Electrification, HVAC-focused and Behavioral and operations retrofit types (roughly 2,100 ft^2), compared with other common types, with floor area typically around 1,700 ft^2. Electrification projects had by far the highest project costs amongst the common retrofit types ($28.35/$ft^2$); Superinsulation projects recorded the highest median costs ($44.47/$ft^2$), but these numbers represent very few projects. These were followed by HVAC-focused ($7.80/ ft^2), Home performance upgrade ($5.24/ ft^2) and Envelope-focused project ($3.15/ ft^2). Many electrification projects included PV panels, which is a potential driver behind some of the higher normalized costs. Incentive fractions were typically very high in the envelope-focused project (60%), while HVAC-focused and Electrification projects had 29 and 25% incentive fractions respectively. It is notable that while Electrification work is a newly emerging trend, with unfamiliar technologies for many contractors and homeowners, the incentives were not particularly high. Electrification projects occurred in only a handful of states, including Massachusetts (n=213), Vermont (n=35), California (n=16), Florida (n=5), Tennessee (n=3) and New Mexico (n=1). The large amounts of electrification projects in MA and VT are due to programs operating in those locations with decarbonization goals, including Home MA DOER – Home MVP and Zero Energy Now.

Table E 2. Retrofit type summary per number of projects.

ENERGY UPGRADE TYPE	Number of Projects	Median Conditioned Floor Area (ft^2)	Median Gross Project Cost ($/$ft^2$)	Median Gross Project Cost ($)	Median Project Incentive ($)	Median Incentive Fraction (%)
Home Performance Upgrade	**1,061**	**1,700 (n=1,028)**	**$5.24 (n=1,028)**	**$9,063 (n=1,053)**	**$1,112 (n=622)**	**15% (n=622)**
Individual Measure	**251**	**1,763 (n=229)**	**$1.84 (n=229)**	**$3,787 (n=250)**	**$666 (n=238)**	**17.9% (n=238)**
Electrification	**294**	**1,985 (n=292)**	**$9.61 (n=292)**	**$18,653 (n=294)**	**$6,213 (n=280)**	**29.8% (n=280)**
HVAC Focused	226	2,080 (n=207)	$7.80 (n=207)	$15,219 (n=223)	$4,746 (n=200)	29% (n=200)
Envelope-Focused	122	1,742 (n=112)	$3.15 (n=112)	$5,877 (n=120)	$3,007 (n=113)	60.7% (n=113)
Behavior and Operational	16	2,028 (n=16)	---	---	---	---
Small Commercial	13	5,391 (n=12)	$17.61 (n=12)	$56,805 (n=13)	---	---
Aligned with Other Remodeling	12	2,094 (n=5)	$13.94 (n=5)	$21,602 (n=5)	$1,248 (n=4)	4.2% (n=4)
Superinsulation	8	2,966 (n=6)	$44.47 (n=6)	$102,456 (n=6)	$22,758 (n=1)	14.4% (n=1)
Over-Time	5	1,637 (n=3)	$31.12 (n=3)	$27,139 (n=3)	$1,366 (n=2)	7% (n=2)
No Response	---	---	---	---	---	---

APPENDIX F – Energy Performance

As summarized in Figure F 1 to Figure F 6, Percent savings distributions were quite consistent across each of the three-energy metrics, with 28% median savings for carbon and energy cost, and 33% median net-site energy savings. For each metric, the maximum apparent savings were around 80%, though 14-25 projects saved >80% for each energy metric. One single project reported 100% net-site savings. Only a relatively small subset of projects achieved >50% reductions: 148 for net-site energy, 121 for energy cost and 97 for carbon.

For comparison, a past meta-analysis of US deep retrofit projects (Less & Walker, 2014) found higher median site energy and cost savings (47% and $1,283, respectively), suggesting that projects were on average less aggressive in this database. This is also evidenced by comparing the total project costs, which were typically $40,420 in the prior review, while being substantially less across the database (see Section 7.1).

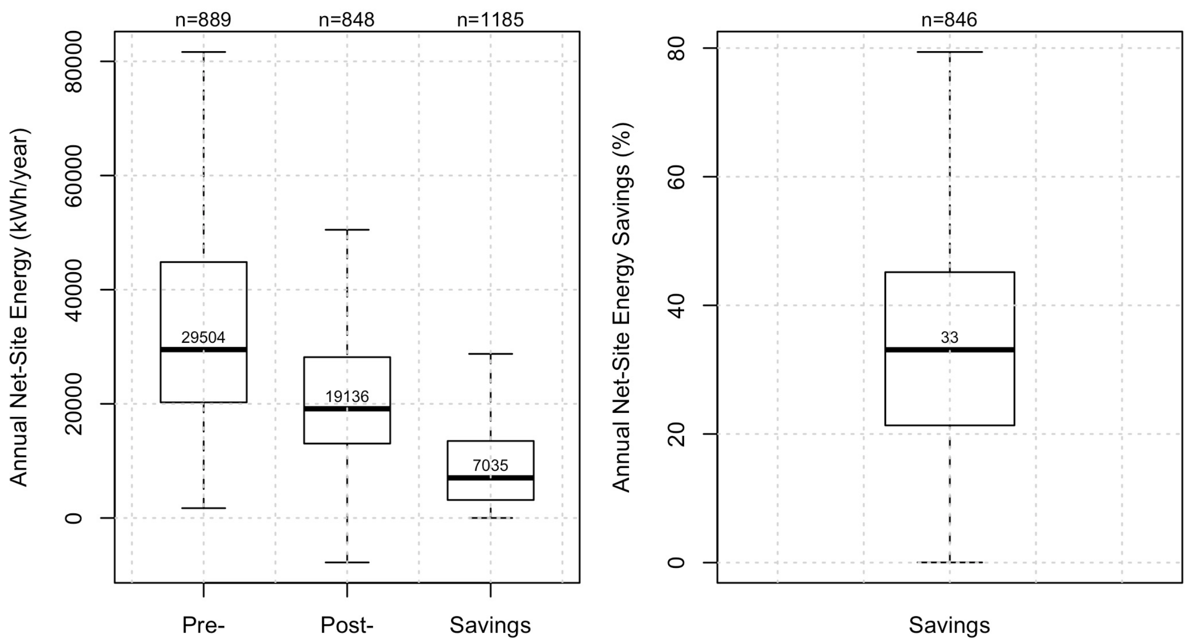


Figure F 1. Annual net-site energy distributions.

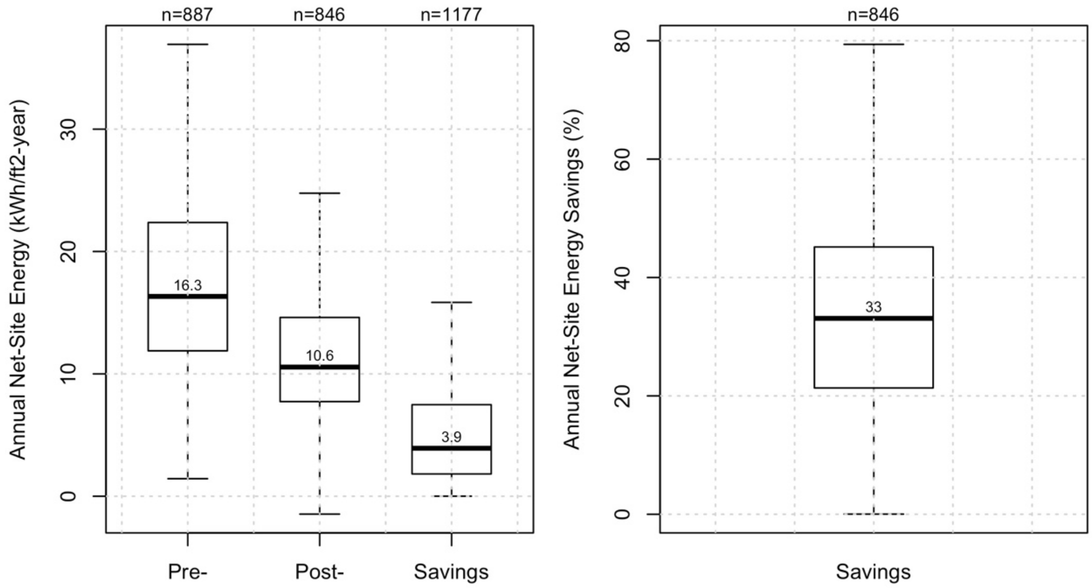


Figure F 2. Annual net-site energy per ft^2 distributions.

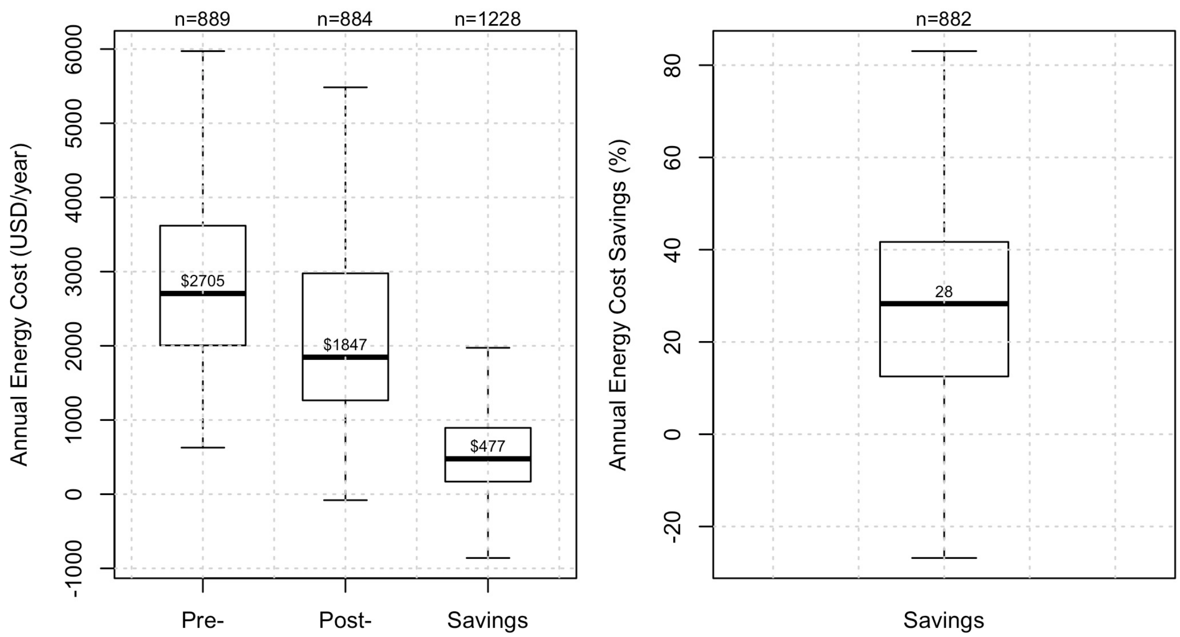


Figure F 3. Annual energy cost distributions.

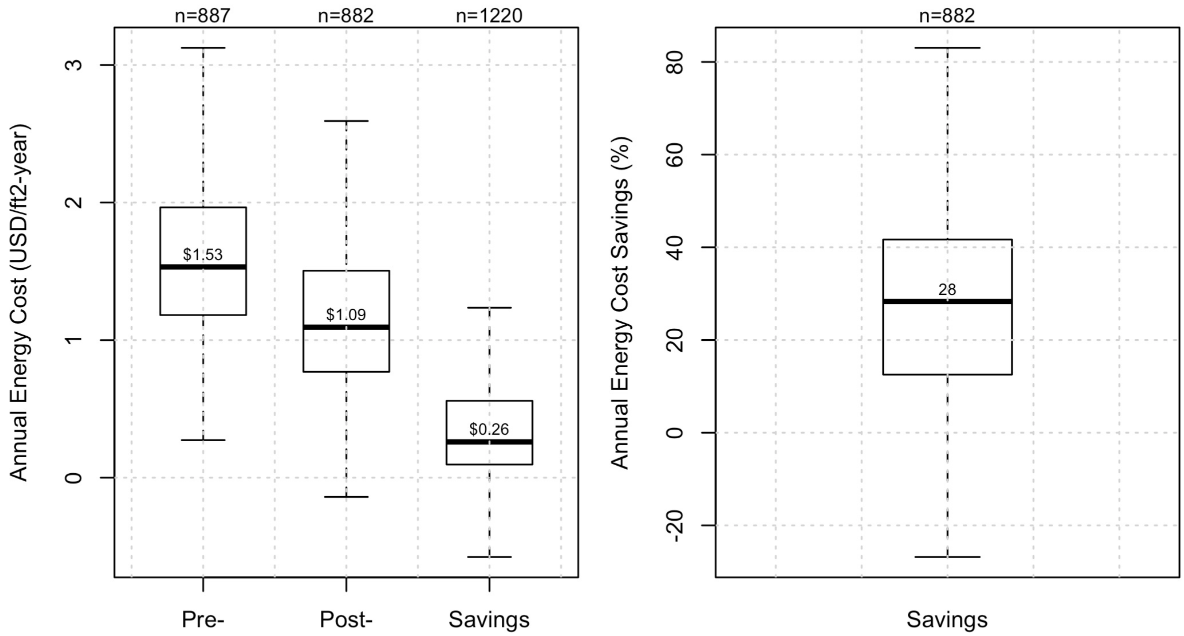


Figure F 4. Annual energy cost per ft² distributions.

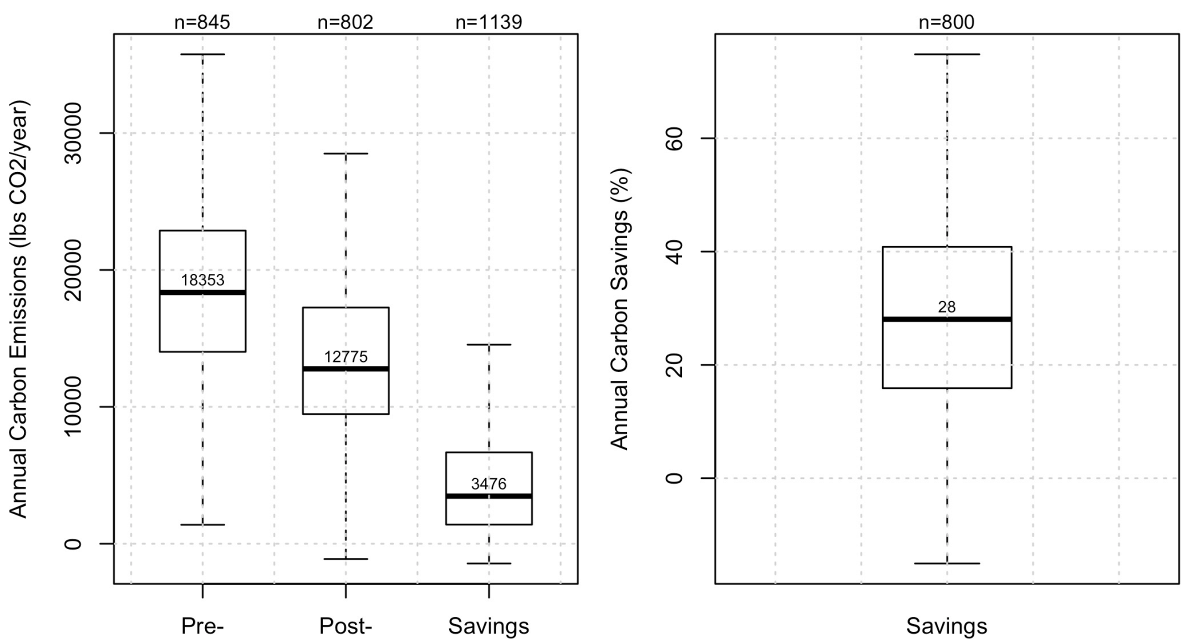


Figure F 5. Annual carbon dioxide equivalent emissions distributions.

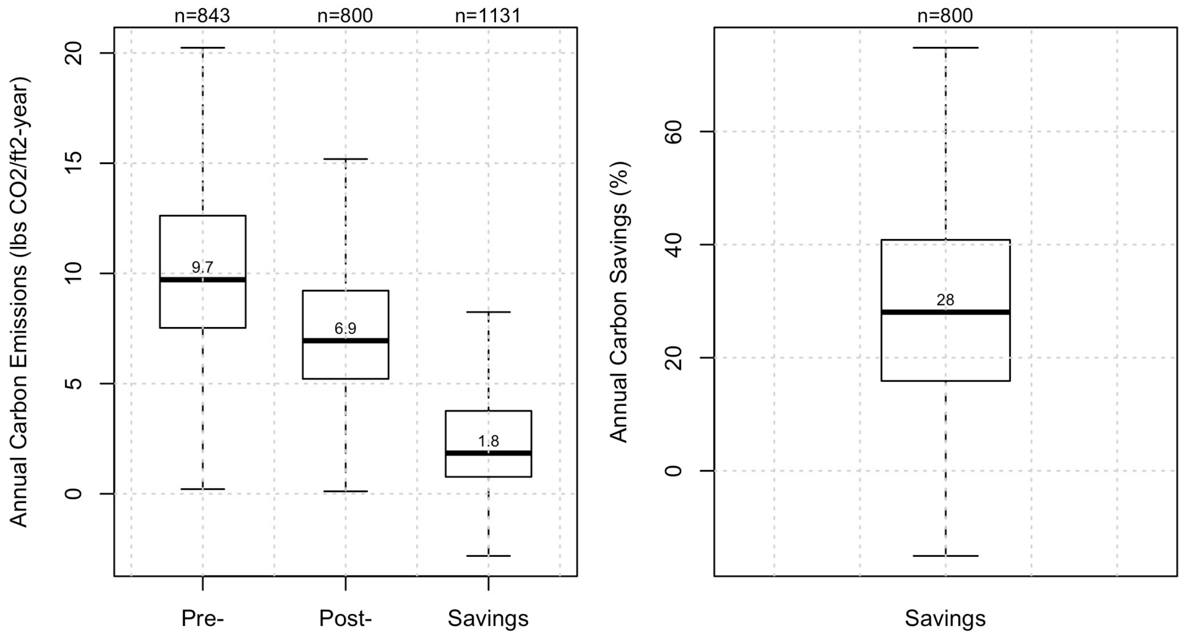


Figure F 6. Annual CO_2e emissions per ft² distributions.

It is critical to note when interpreting these plots that each boxplot does not represent the same dwellings (though there is substantial overlap). The result is that the difference in the median pre- and post- is 10,368 kWh, while the median Savings were 7,035 kWh. Slightly over 300 projects reported savings, but not pre- or post-retrofit usage.

The results above combined electric and natural gas use. If we look at the electricity savings in kWh per site project the mean is 1,271 kWh and the median is about 298 (n=995). Figure F 7 shows the spread of these results and, more importantly, shows that many sites increased energy use due to electrification.

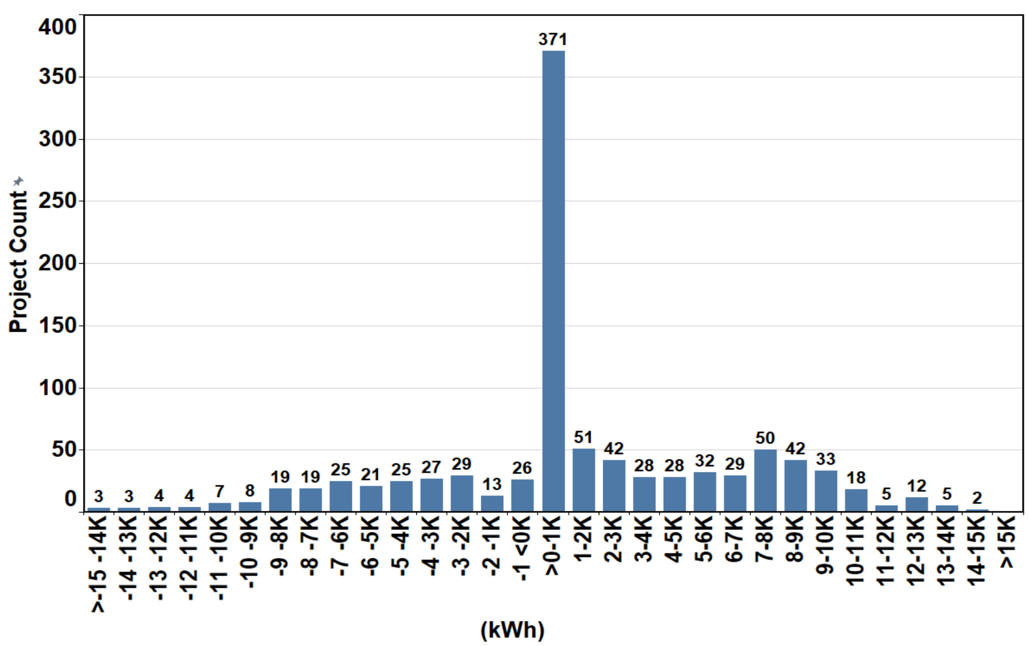


Figure F 7. Electricity savings (kWh) per site project. (n=995)

[Figure F 8](#) shows the distribution of natural gas savings (in kWh). The mean savings are 12,945 kWh with a median of 6,228 kWh (n=732).

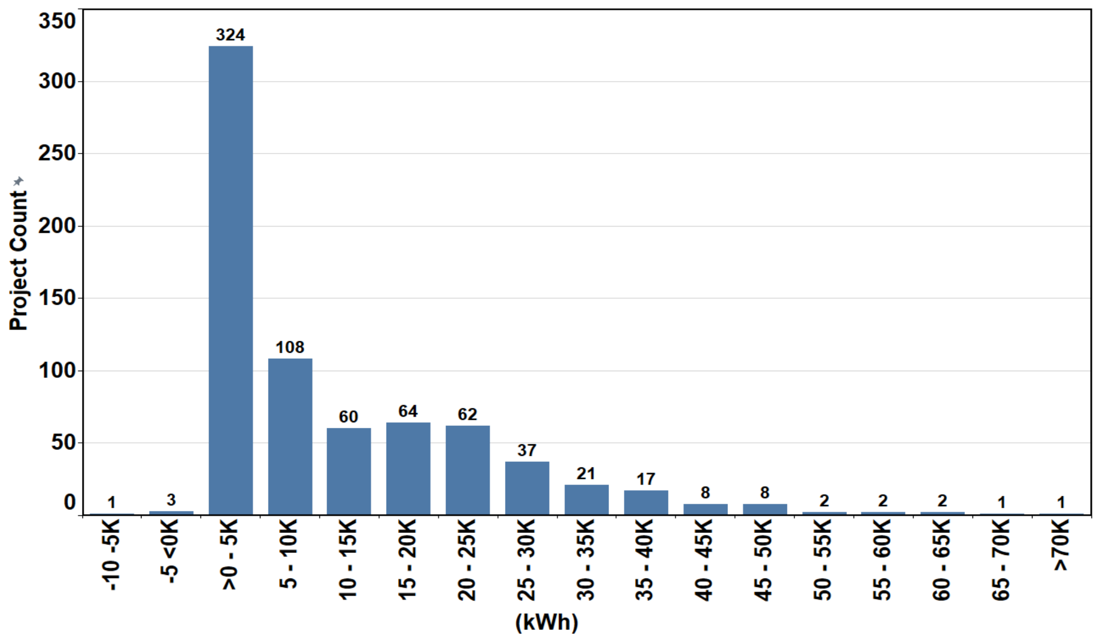


Figure F 8. Natural gas savings (kWh) per site project. (n=732)

Figure F 9 presents the distribution of carbon emissions savings per project in lbs. CO_2. The mean of the total lbs. CO_2 savings of the gathered DER projects are about 5,056 lbs. CO_2 and a median of 3,476 lbs. CO_2 (n=1,139). Resulting in a mean of about 2.79 lbs. CO_2 /ft^2 and a median of 1.85 lbs. CO2 /ft^2 (n=1,131), as shown in Figure F 10. The cost on energy savings per project site has a mean of about $680 and a median of $477 (n=1,228). Resulting in a mean of 0.28 $/ft^2 and a median of 0.12 $/ft^2 (n =1,657). The distribution of CO_2e (lbs./kWh) per site project (n=1,239), results in a mean of 0.67 lbs./kWh and a median of 0.73 lbs./kWh.

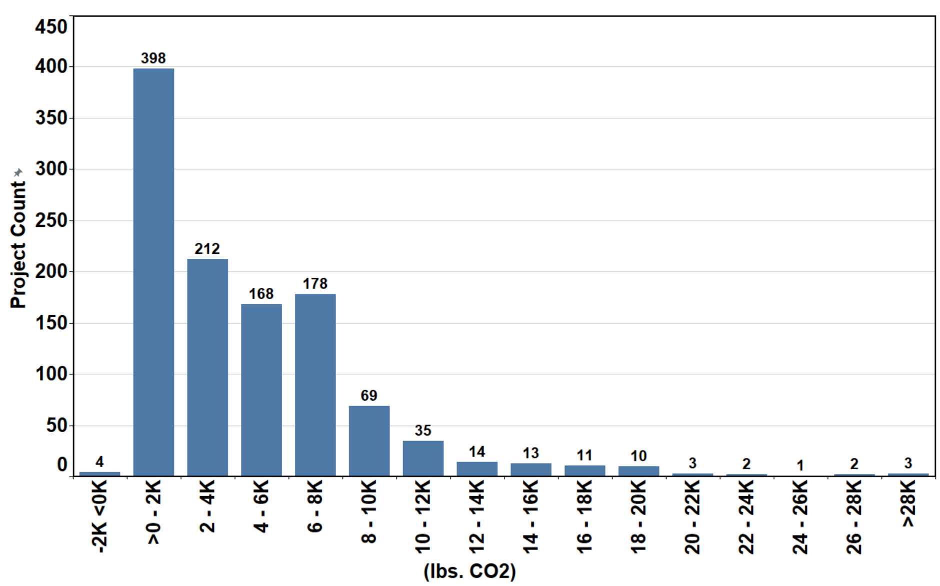


Figure F 9. Savings in carbon emission per (lbs. CO_2) per site project. (n=1,139)

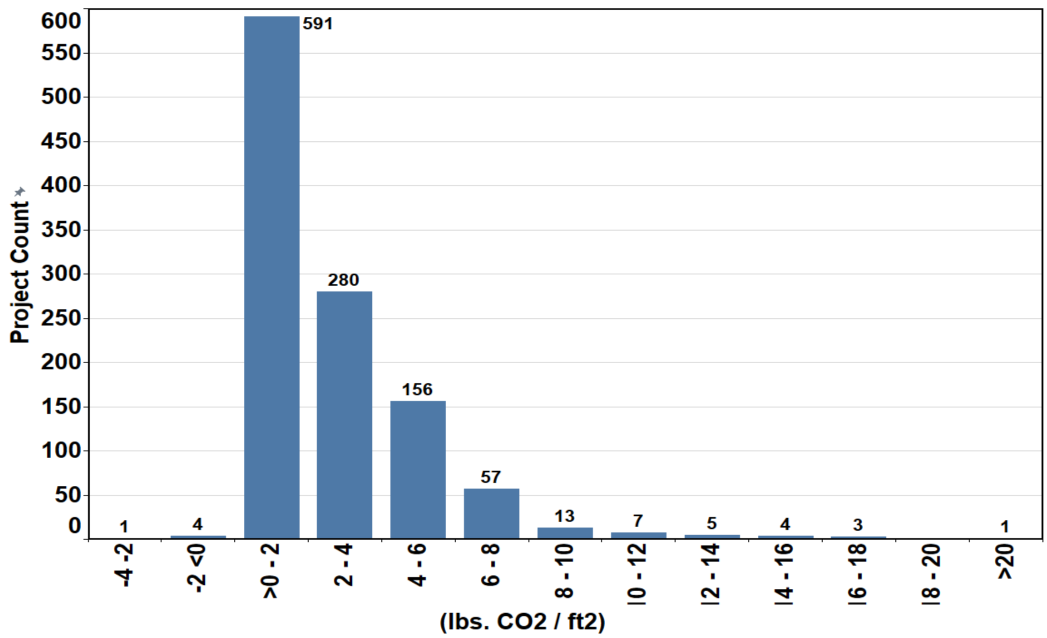


Figure F 10. Savings in carbon emission per (lbs. CO_2/ft^2) per site project. (n=1,131)

F.1 Energy Performance - Electricity

If we look at the savings in carbon emissions (lbs. CO_2) per site project by fuel, electricity has a mean of about 1,069 lbs. CO_2 and a median of 129 lbs. CO_2 (n= 996) Figure F 11. Resulting in a mean of 0.79 lbs. CO_2/ft^2 and a median of 0.08 lbs. CO_2/ft^2 (n=992) Figure F 12.

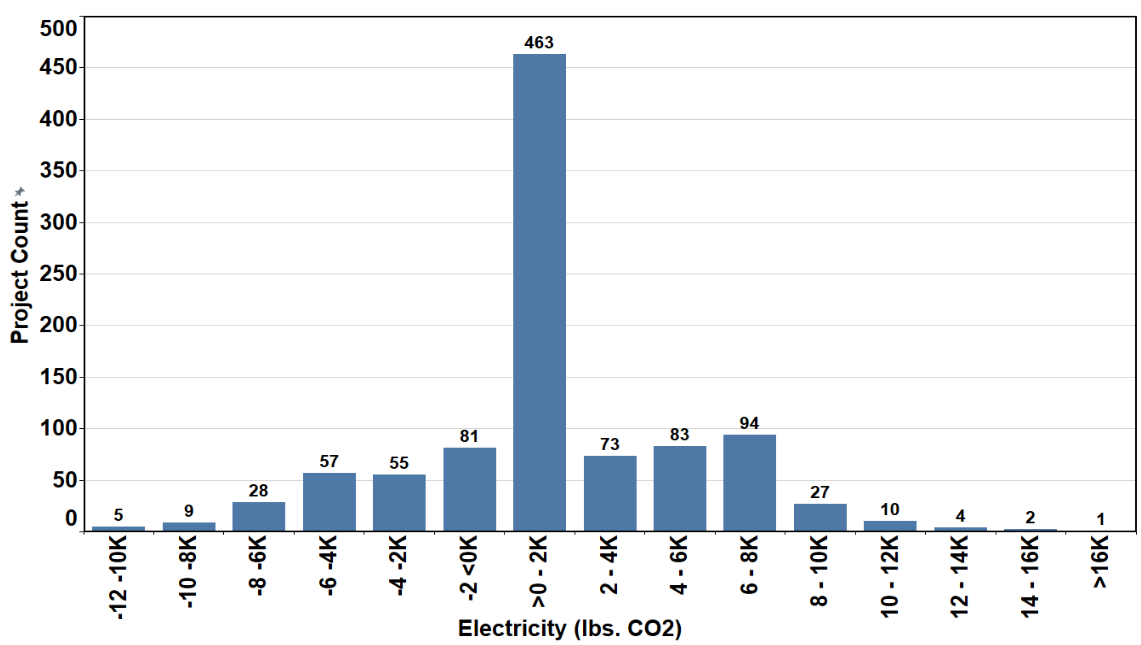


Figure F 11. Electricity, savings in carbon emission per (lbs. CO_2) per site project. (n=996)

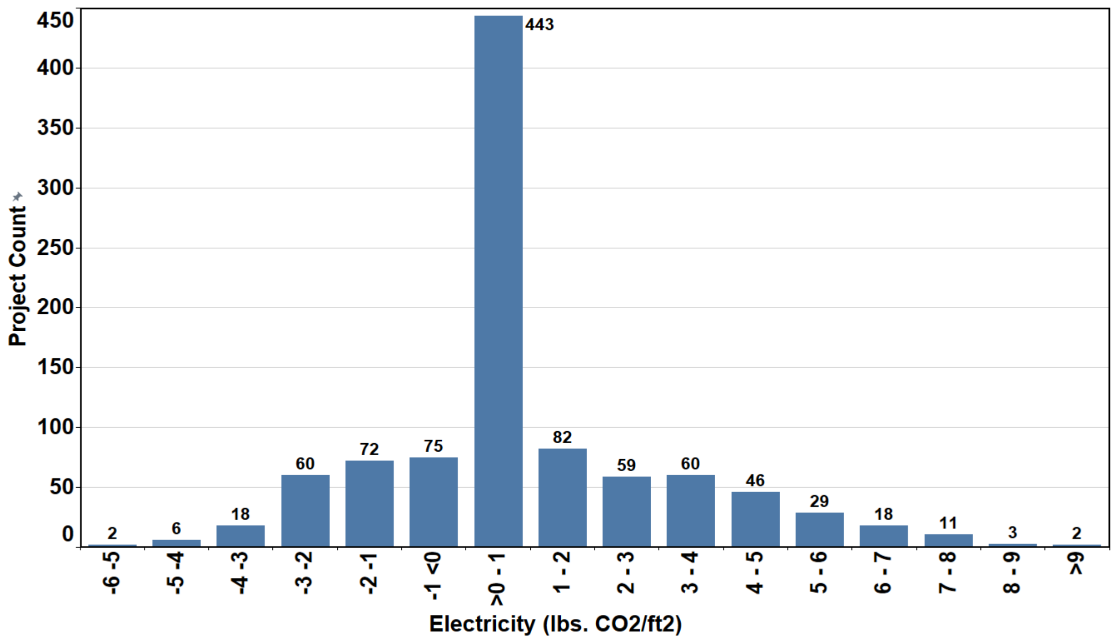


Figure F 12. Electricity, savings in carbon emission per (lbs. CO_2/ft^2) per site project. (n=992)

F.2 Regression Modeling of Energy and Carbon Savings

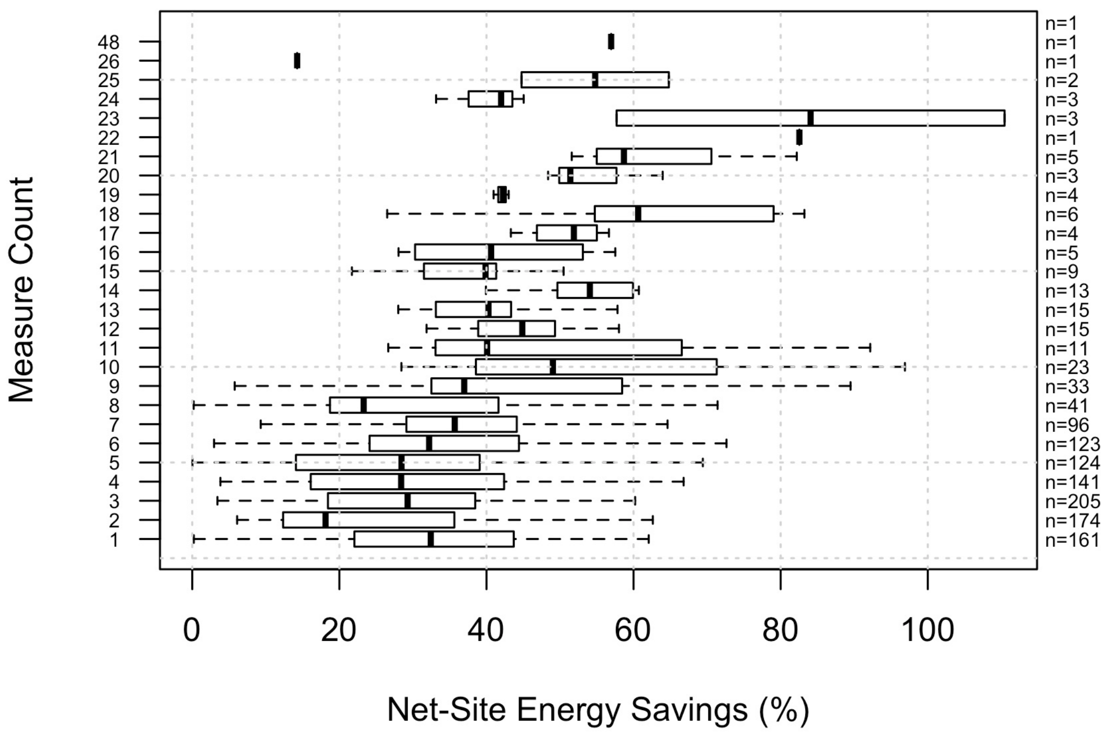


Figure F 13. Measure count and associated net-site energy savings distributions.

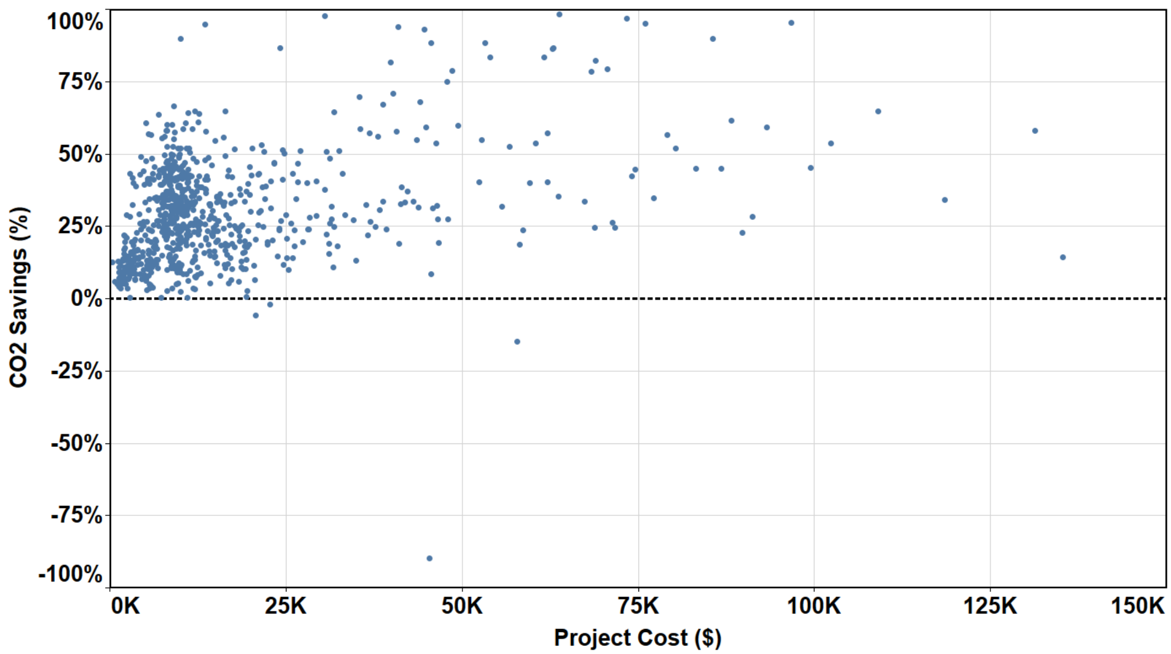


Figure F 14. Total project cost ($) vs %$CO_2$ site energy savings.

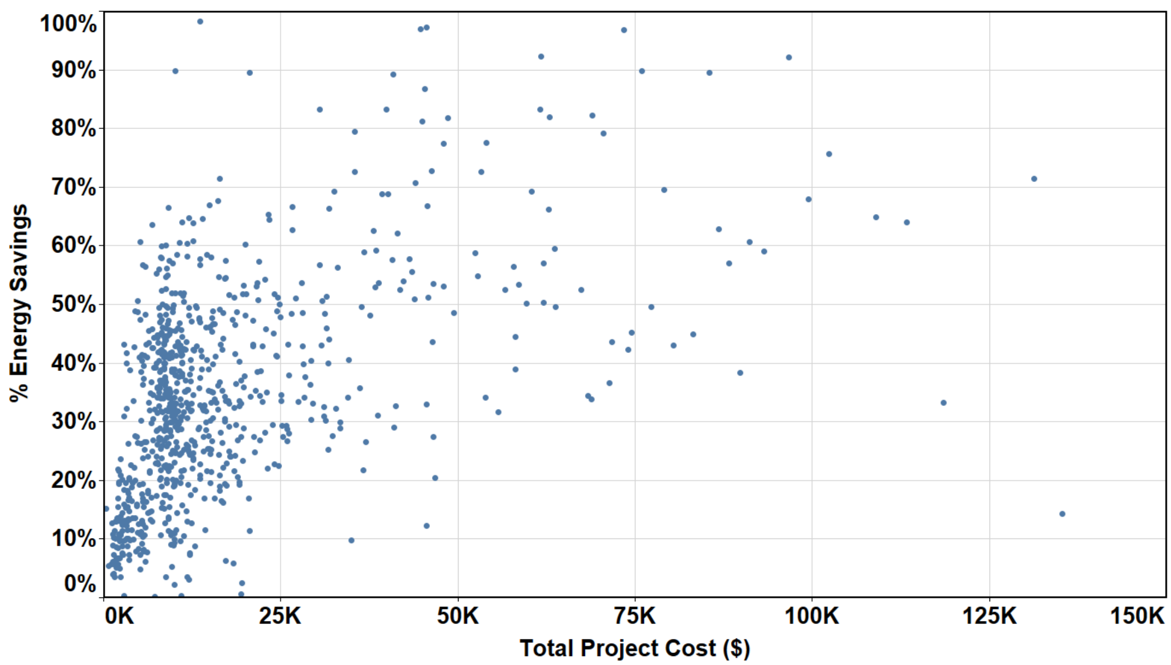


Figure F 15. Total project cost ($) vs % energy savings.

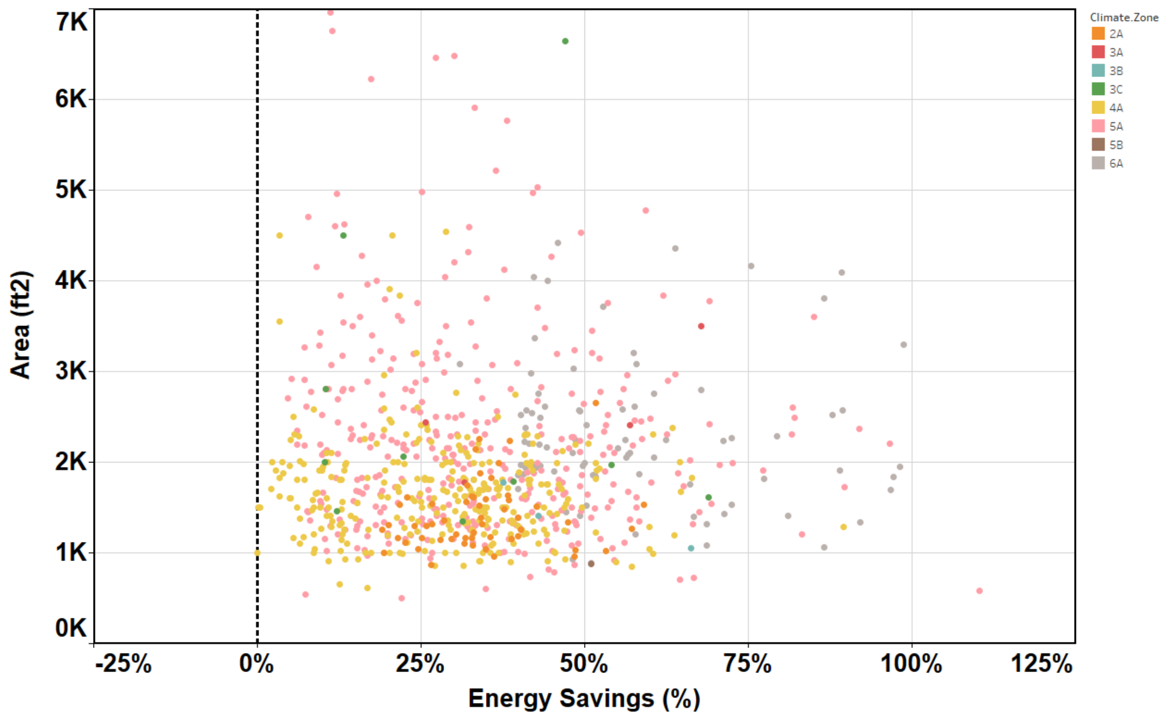


Figure F 16. Energy savings (%) vs area (ft²) per climate zone.

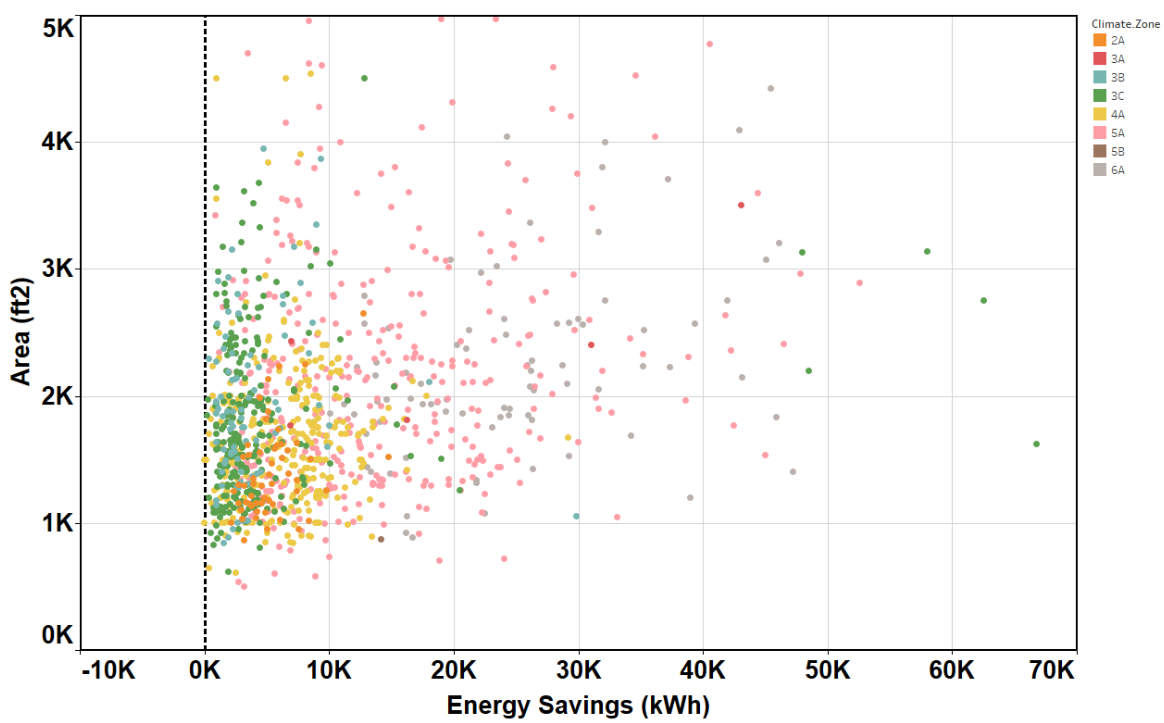


Figure F 17. Energy savings (kWh) vs area (ft²) per climate zone.

F.3 Financing and Cash Flow

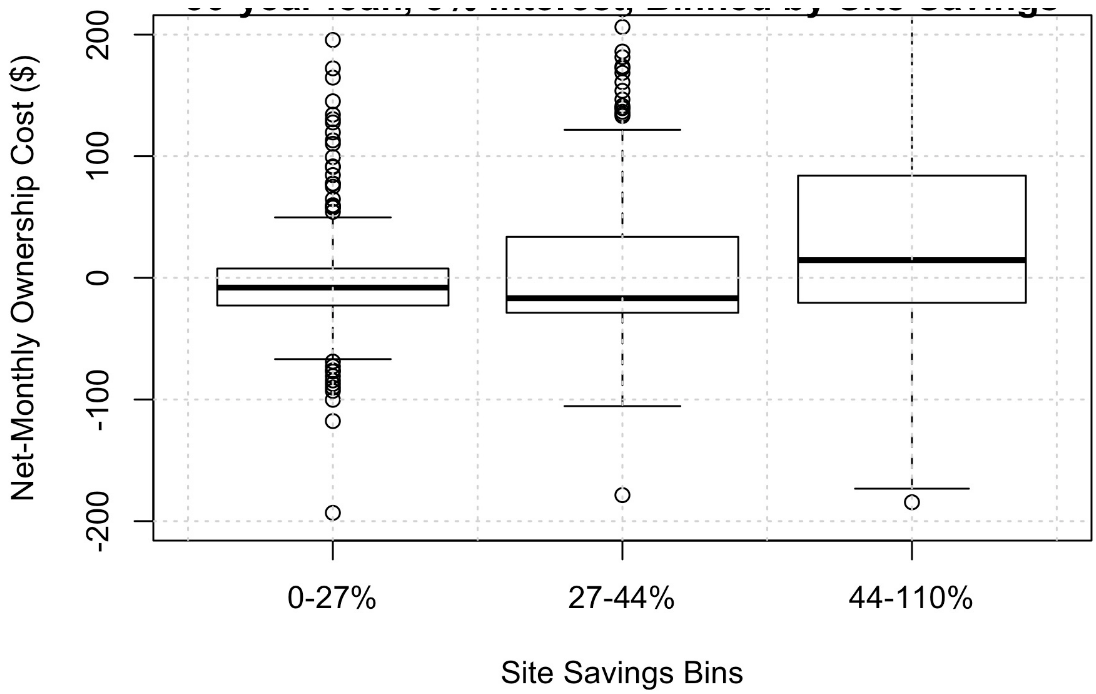


Figure F 18. Net-monthly cost of homeownership (30-year, 3.0%), binned by net-site energy savings.

APPENDIX G – Measure Costs

This appendix presents the measure costs recorded in the deep retrofit database. It is presented both on terms of "Actions" and "Sections". Action breakdowns included Install, Insulate, Test, Commission, Rebate, etc. Section breakdowns more align with individual measures and begin with "HVAC" in this appendix. Results for measures where 10 or more instances were recorded are included in the summary plots.

G.1 Install

The install action measures are summarized in Figure G 1, and the floor area normalized cost summaries are shown in Figure G 2. The install measures are sorted by the median reported costs, and the number of costed measures is listed on the second y-axis. The most frequent install measures were *HVAC_Heat pump, HVAC_Heating, HVAC_Thermostat, Electrical_Lighting and HVAC_Ducts*. Notably, the PV costs reported in these plots show the costs recorded for all systems in the database from roughly 2010 to 2020. The cost of PV has reduced dramatically over that time period, so these numbers are biased high relative to current prices.

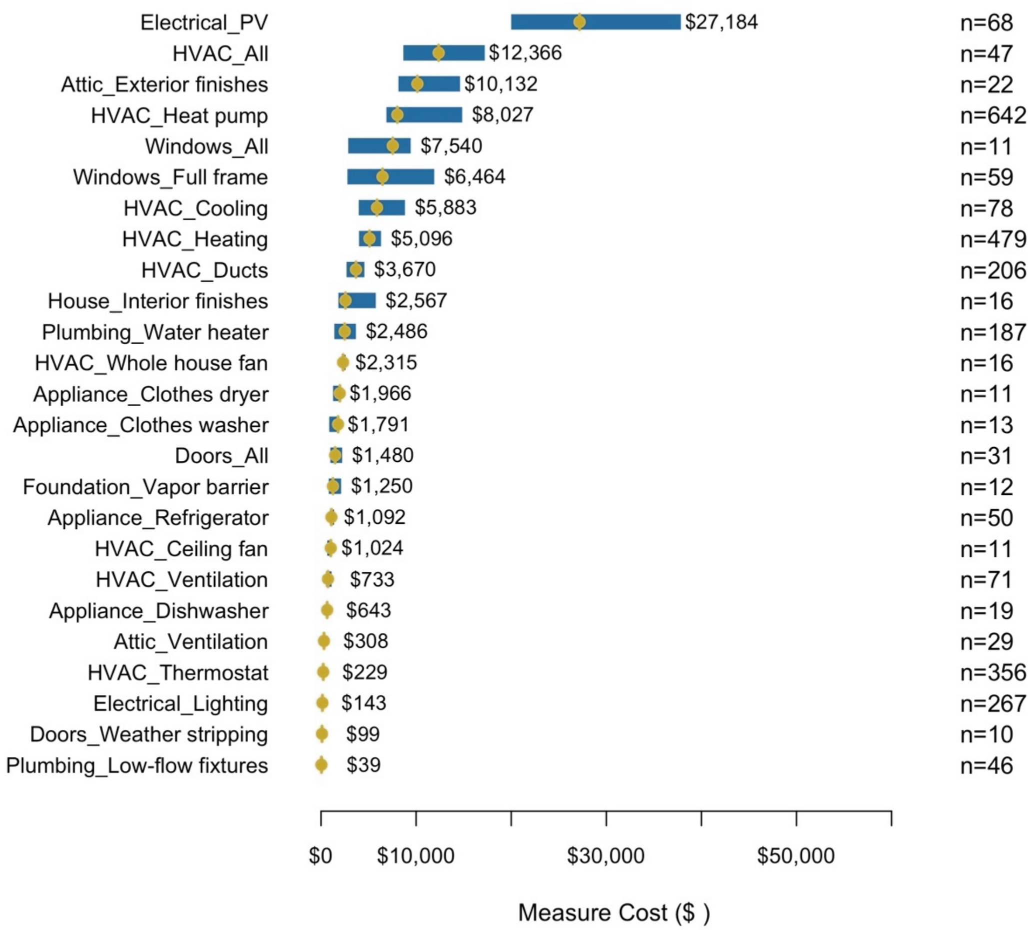


Figure G 1. Installation cost distributions.

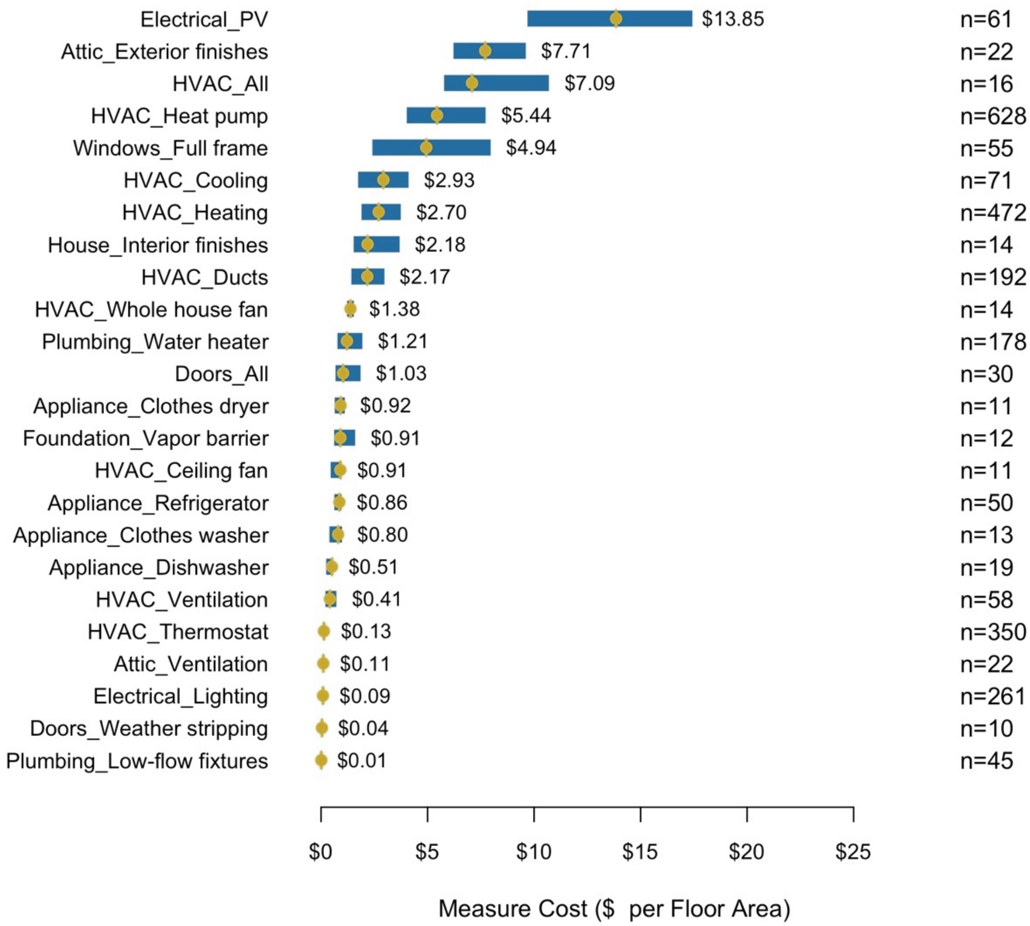


Figure G 2. Installation cost distributions per dwelling floor area.

G.2 Insulation

The Insulate action measures are split out by what part of the envelope is being insulated in Figure G 3, and these measures are normalized by the treated surface area in Figure G 4 and by treated surface area per R-value in Figure G 5. The insulate measures are sorted by the median reported costs, and the number of costed measures is listed on the second y-axis. The most frequent insulate measures were *Attic_Framed floor, Walls, Attic_Roof, Foundation_Band joist, Foundation_Framed floor, and Foundation_Basement walls*. The median total measure costs across these varied assemblies are remarkably consistent, varying only from $1,544 for the basement walls to $2,106 for walls. When normalized by treated surface area, the assemblies are distributed into low-cost (walls, attic knee wall and attic framed floor) and high-cost assemblies (Foundation band joist, framed floor, basement walls and attic roof). The high-cost insulation measures are distinguished in two ways. First, a substantial number of those assemblies were insulated with higher-cost insulation materials (e.g., closed cell spray foam). Second, the assemblies are either insulated against gravity (e.g., attic roof or foundation framed floor) or on basement walls without easy cavities to fill.

Figure G 3. Insulation cost distributions.

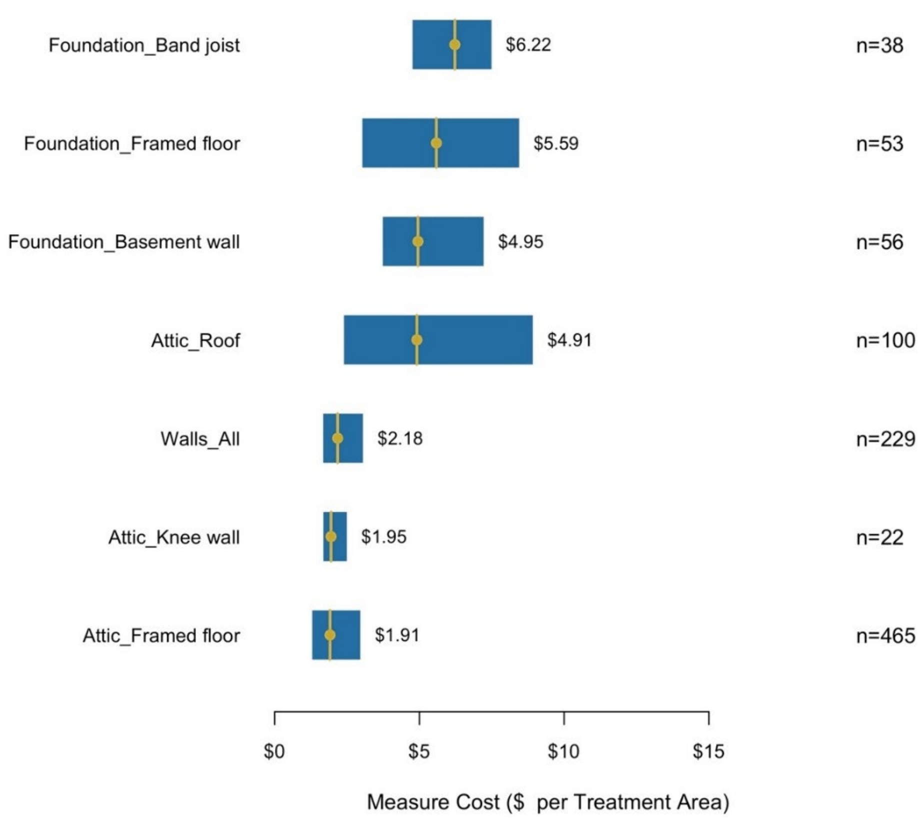


Figure G 4. Insulation cost distributions per treatment area.

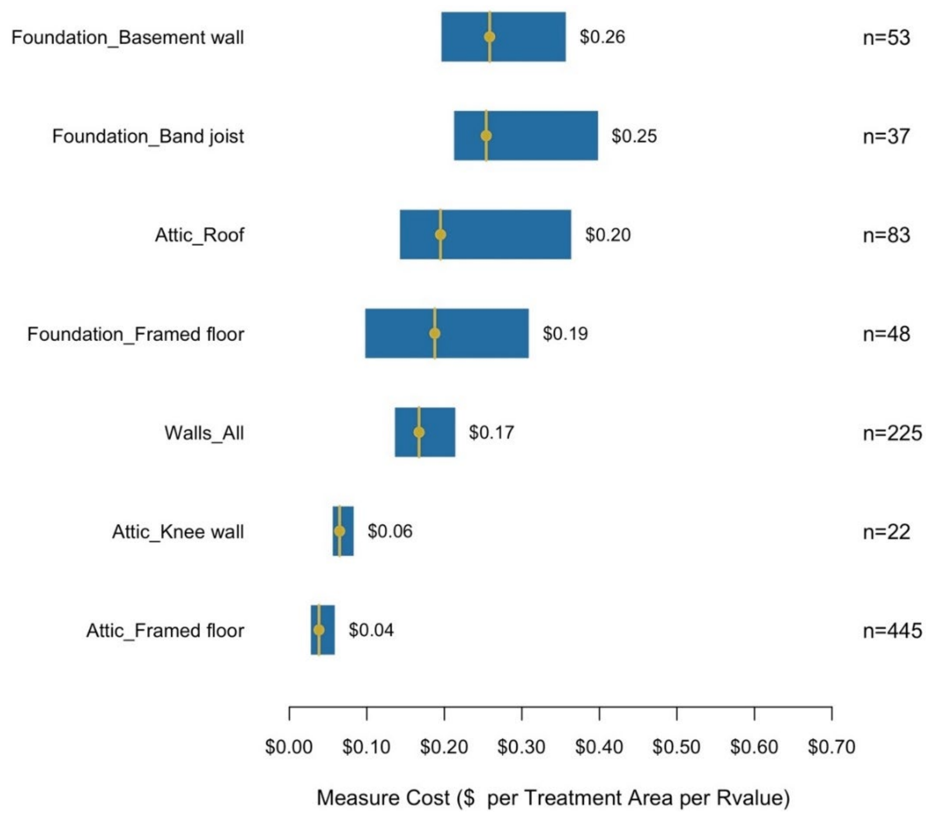


Figure G 5. Insulation cost distributions per treatment area per R-value.

G.3 Seal

The Seal measure costs are summarized in Figure G 6, and these are normalized by dwelling floor area in Figure G 7. Three sealing measures were recorded in the database, including sealing the House_Envelope, HVAC_Ducts and Attic_All. House and Duct sealing were the most common sealing measures recorded. For similar costs, duct leakage was able to be reduced two-fold more than envelope leakage, which likely makes it much more cost-effective in dwellings with ducts outside of conditioned space. For both ducts and envelope, the relationship between the percent reductions achieved and the reported measure costs are extremely weak.

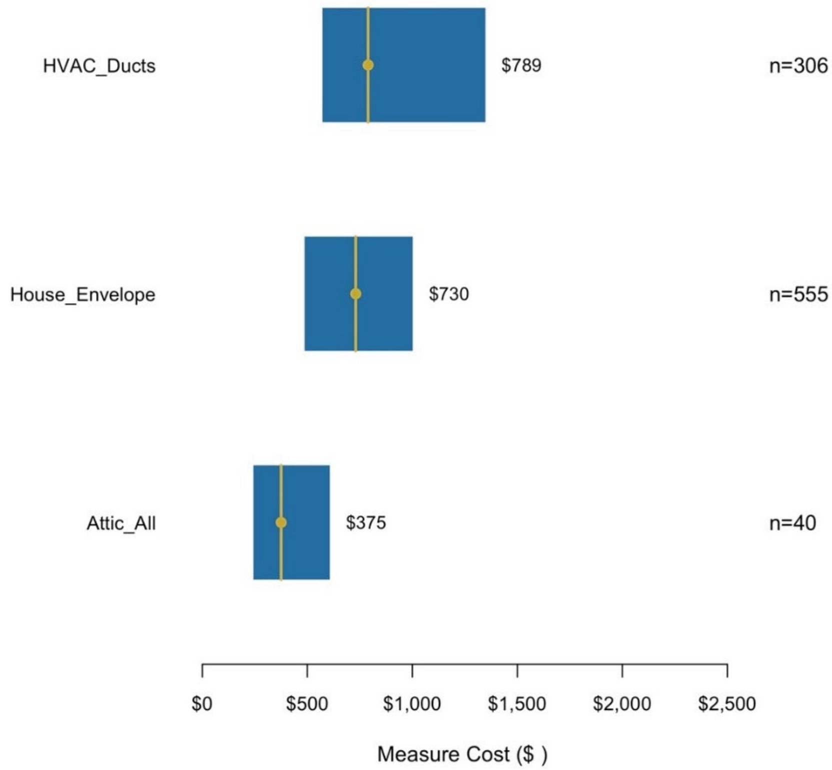


Figure G 6. Sealing cost distributions.

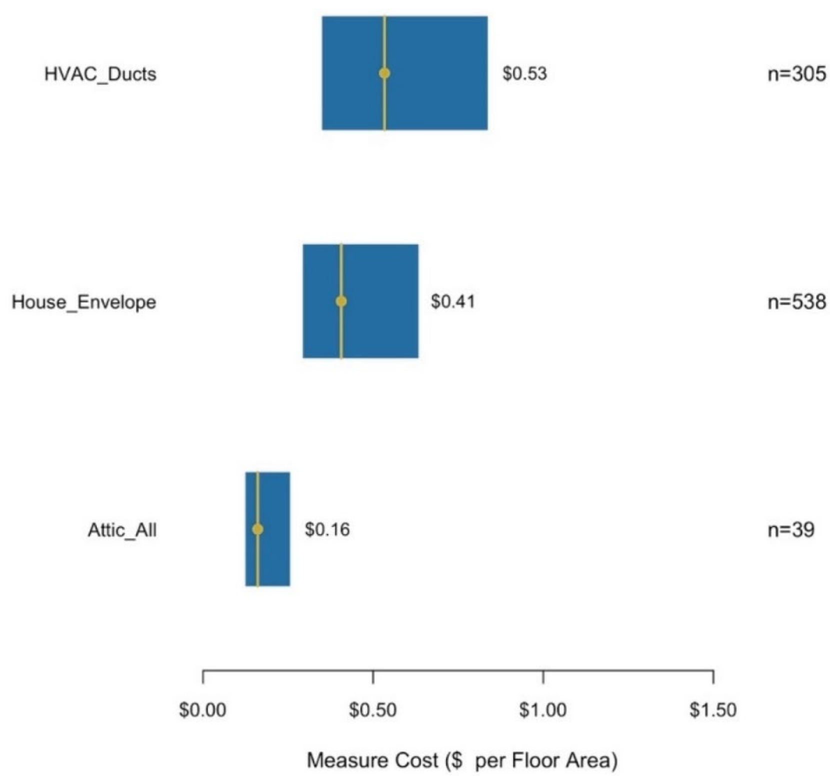


Figure G 7. Sealing cost distributions per dwelling floor area.

G.4 Test and Commission

The Test action cost summaries are shown in Figure G 8. Overall, both testing and commissioning costs were infrequently reported and were inexpensive. Testing measures recorded in the database included only combustion safety testing and HERS rating test-out procedures. Commissioning measures were recorded solely for blower door testing the *House_Envelope*. These were only recorded by one program, which had consistent and low testing costs of $78 per house.

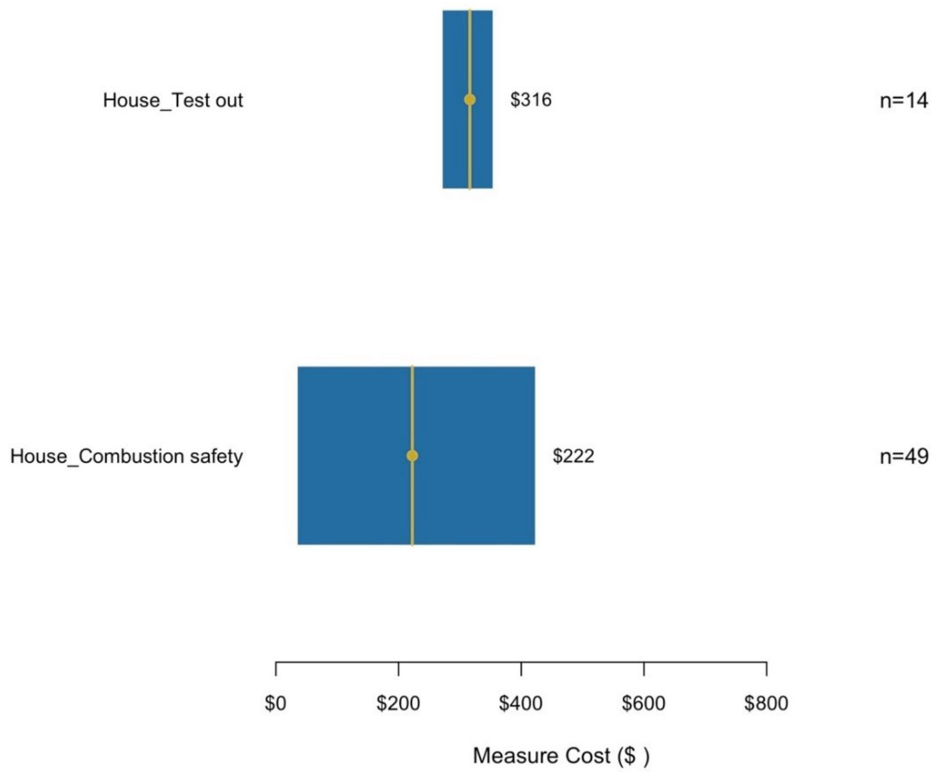


Figure G 8. Testing costs.

G.5 Demo and Disposal

Demo and disposal actions were very infrequently reported in the database, but when reported, they could be substantial costs, as reflected in the summary plot in Figure G 9. These costs were dominated by insulation removal from attic framed floors, and from removal of asbestos contaminated products. The cost of insulation removal ($1,608) is roughly equivalent to the cost of new attic framed floor insulation ($1,827), which means the decision to remove insulation could effectively double the project costs. This should only be done when contamination levels are unacceptable, or when other activities, such as air sealing or wiring addition/replacement is impossible with existing insulation in place.

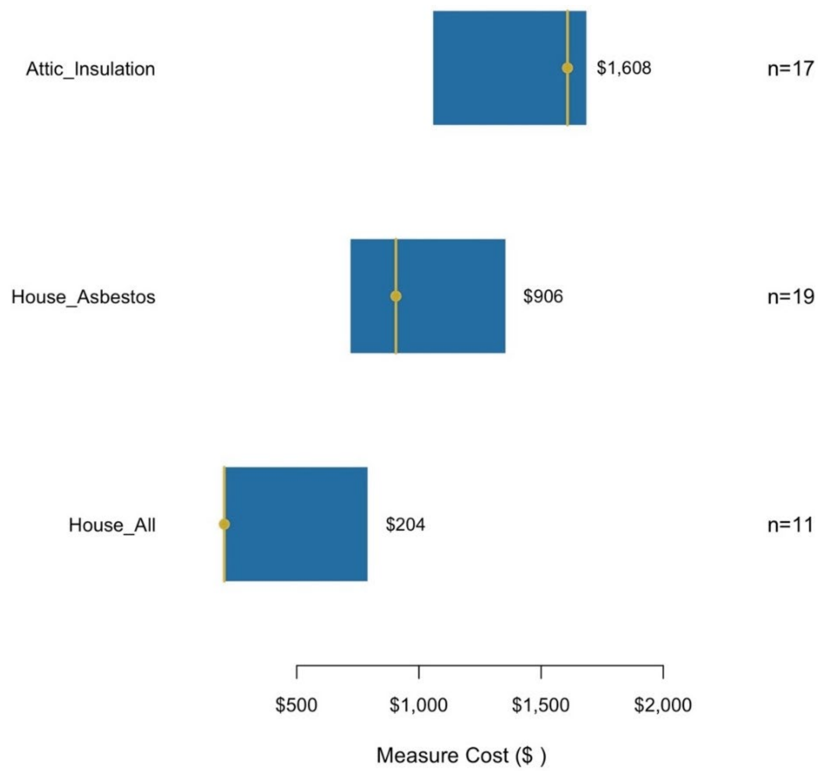


Figure G 9. Demolition and disposal costs.

G.6 Reconfigure

The Reconfigure action was intended to be used for wholesale changes to the boundaries of the building envelope or its systems. It was used very infrequently, in part because of few reconfigurations works in the retrofit projects submitted, but also due to likely categorization of measures in other ways. For example, conversion from a vented to a sealed attic space may have just been recorded as an *Attic_Insulate_Roof* measure. The reconfigure efforts recorded were for foundation conversions from vented to sealed crawlspaces or from unconditioned to conditioned basements. These are summarized in Figure G 10. Floor area normalized costs averaged $1.31 per ft^2, with an interquartile range of roughly $0.50 to $3.50 per ft^2.

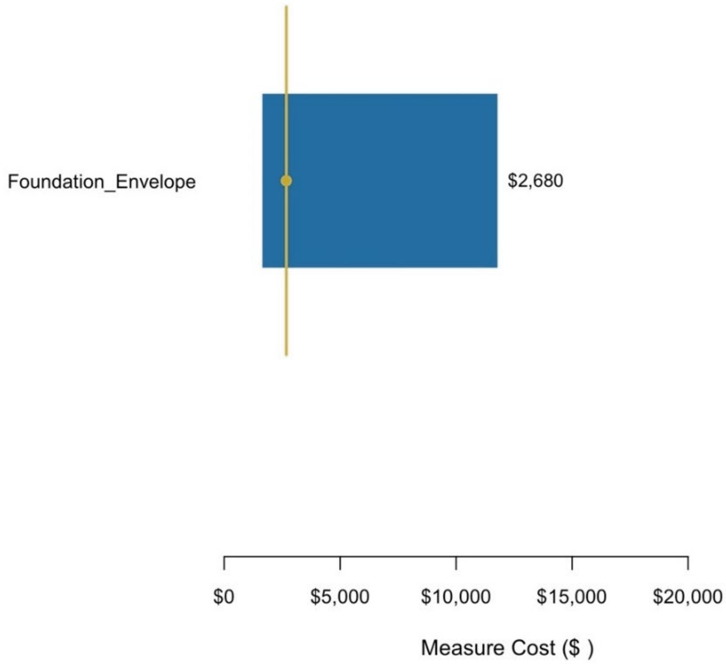


Figure G 10. Reconfigure envelope costs.

G.7 HVAC

Overall, 2,298 costed measures were recorded in the HVAC section, totaling $14.2 million (2019 $USD). The distribution of total costs recorded in the HVAC section are shown in Figure G 11. The floor area normalized HVAC costs are summarized in Figure G 12. The heat pump, heating and cooling system installation costs are normalized by system capacity in Figure G 13.

The most frequently recorded HVAC measures were installation of heat pumps, heating, thermostats and ducts. Of these, the heat pumps had the highest median costs, and traditional fuel-fired heating systems averaged $3,000 less than heat pump installations. Installation of mechanical ventilation and cooling equipment were recorded less frequently, though still represent important costs in retrofit projects. These component types are addressed in sub-sections below.

Notably, the HVAC installation cost per ton show that non-heat pump heating equipment (predominantly gas fired furnaces) have much lower costs per capacity than heat pumps ($953 vs. $3,387). This is partly due to much higher capacity units being installed for gas-fired heating equipment, because gas furnaces are not commonly available in the 12-48 kBtu/hr. size range. The total installed costs for these different technologies show that heat pumps are more expensive ($8,027 vs. $5,096), but not at the more than 3-to-1 cost ratio shown in the $/ton plot.

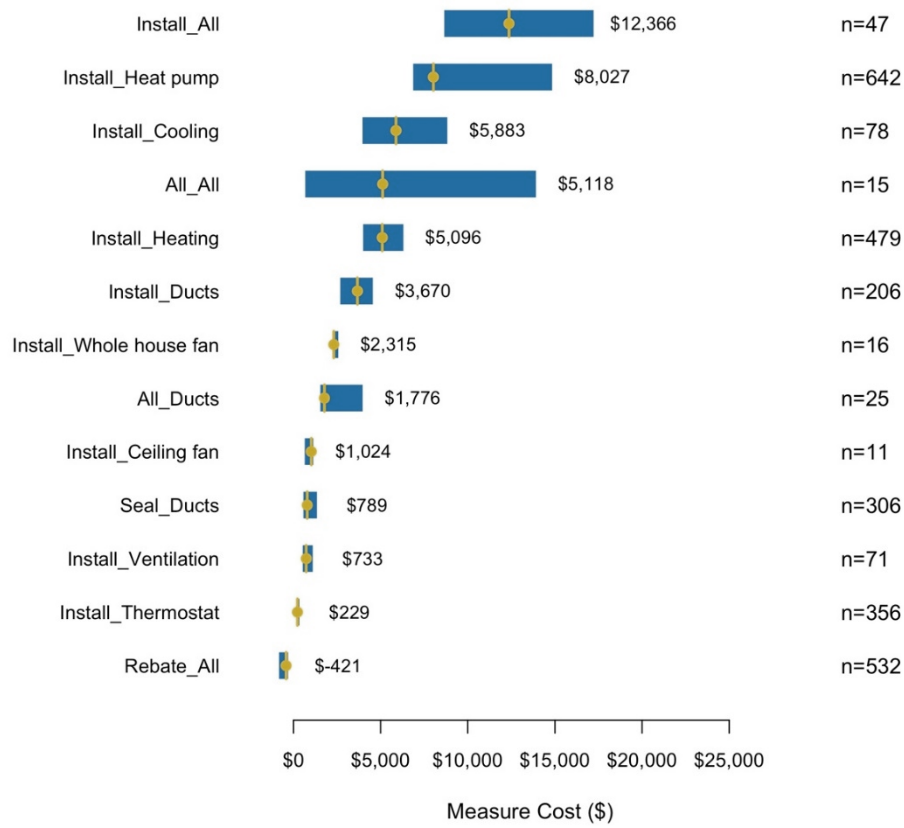


Figure G 11. HVAC installation cost distributions.

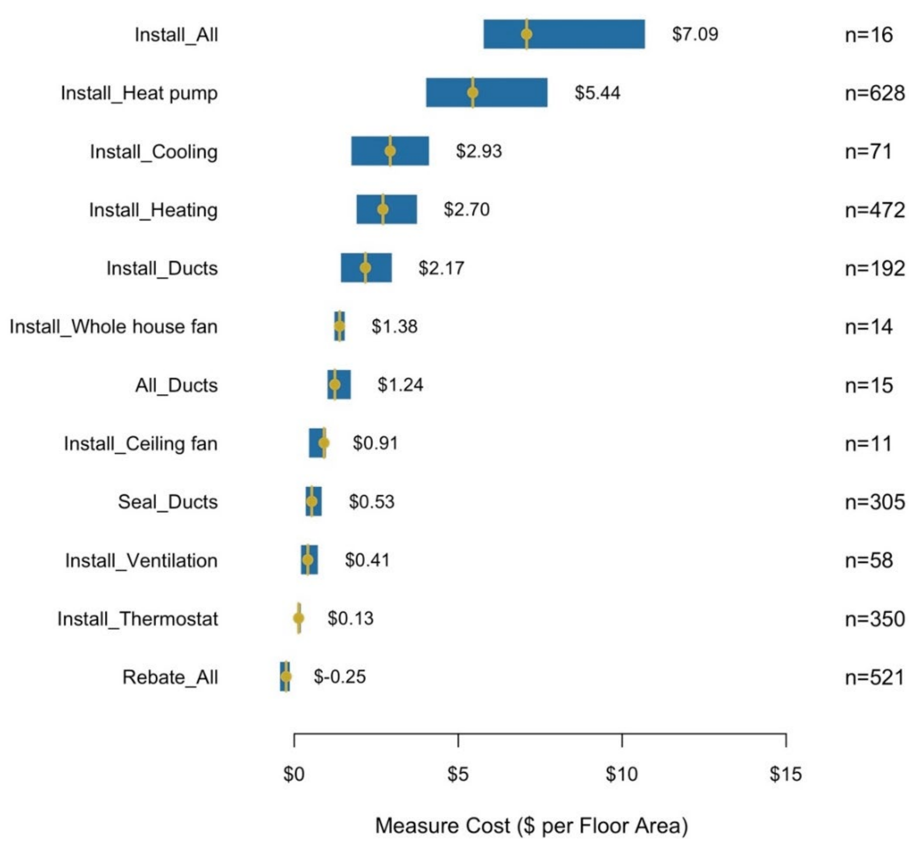


Figure G 12. HVAC installation costs per dwelling floor area.

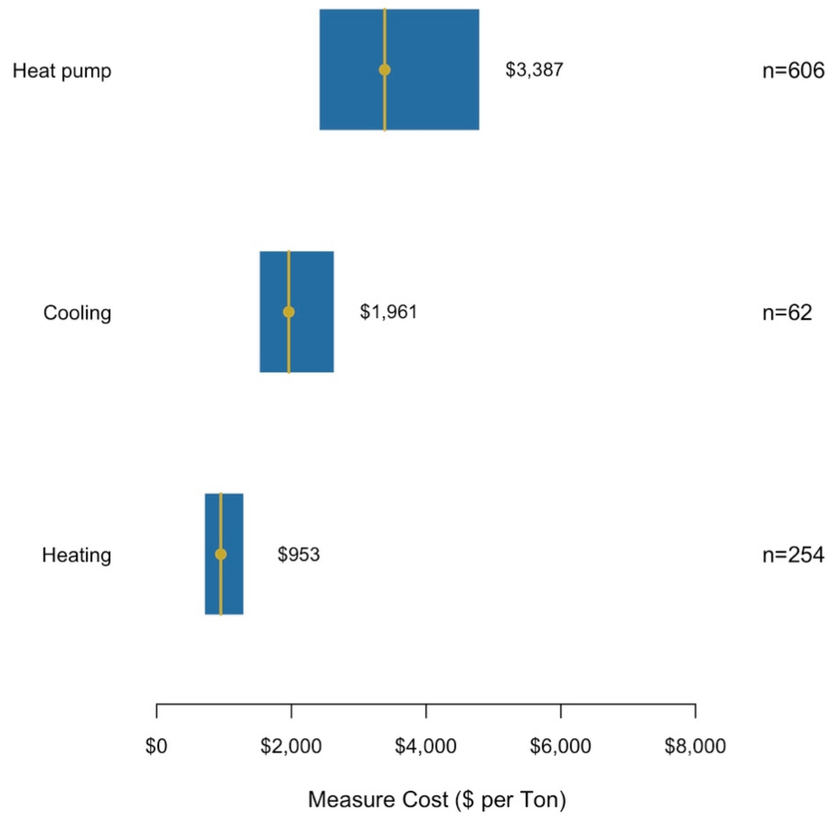


Figure G 13. HVAC installation costs per ton of installed capacity.

G.7.1 Heat Pump

A total of 642 heat pump installations were recorded in the database, with a median cost of $8,027. The median normalized costs were $5.44 per ft^2 and $3,387 per ton.

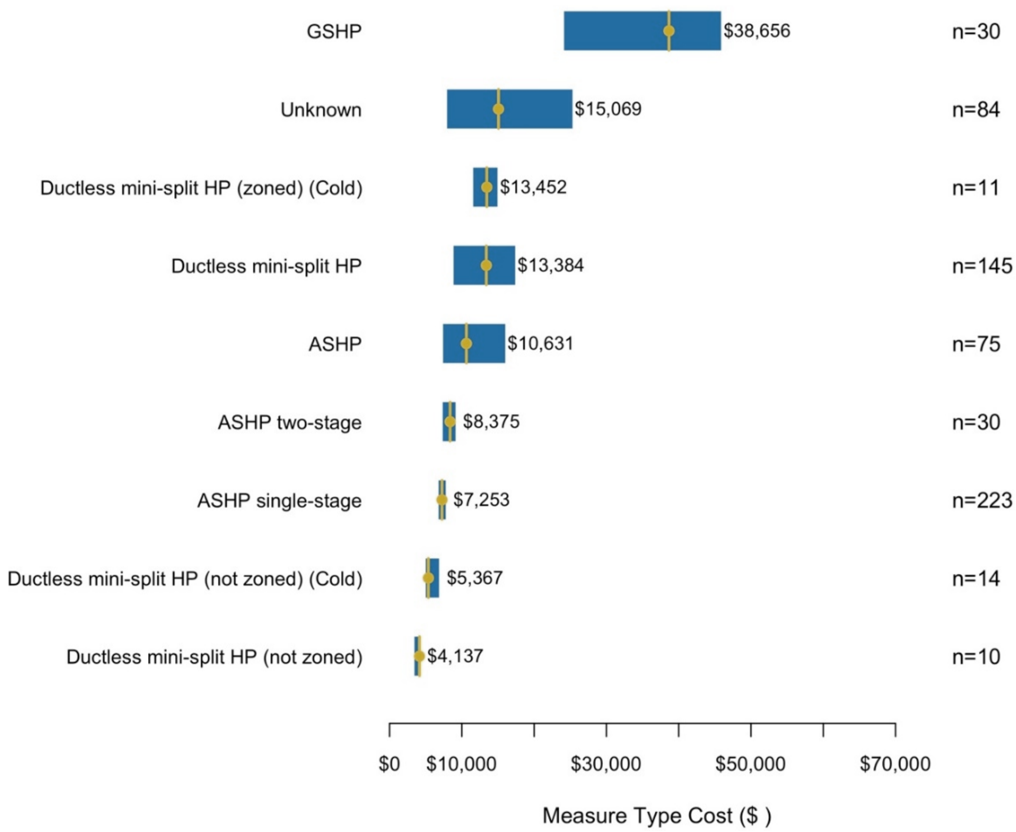


Figure G 14. Heat pump installation cost distributions.

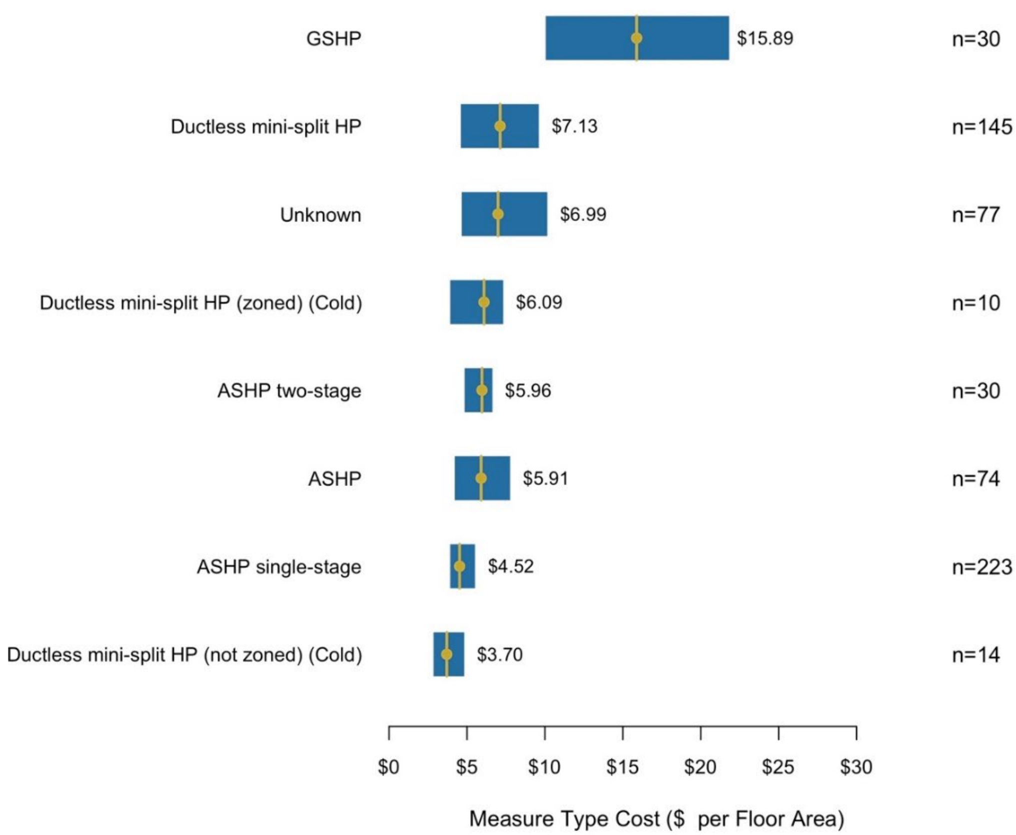


Figure G 15. Heat pump installation costs per dwelling floor area.

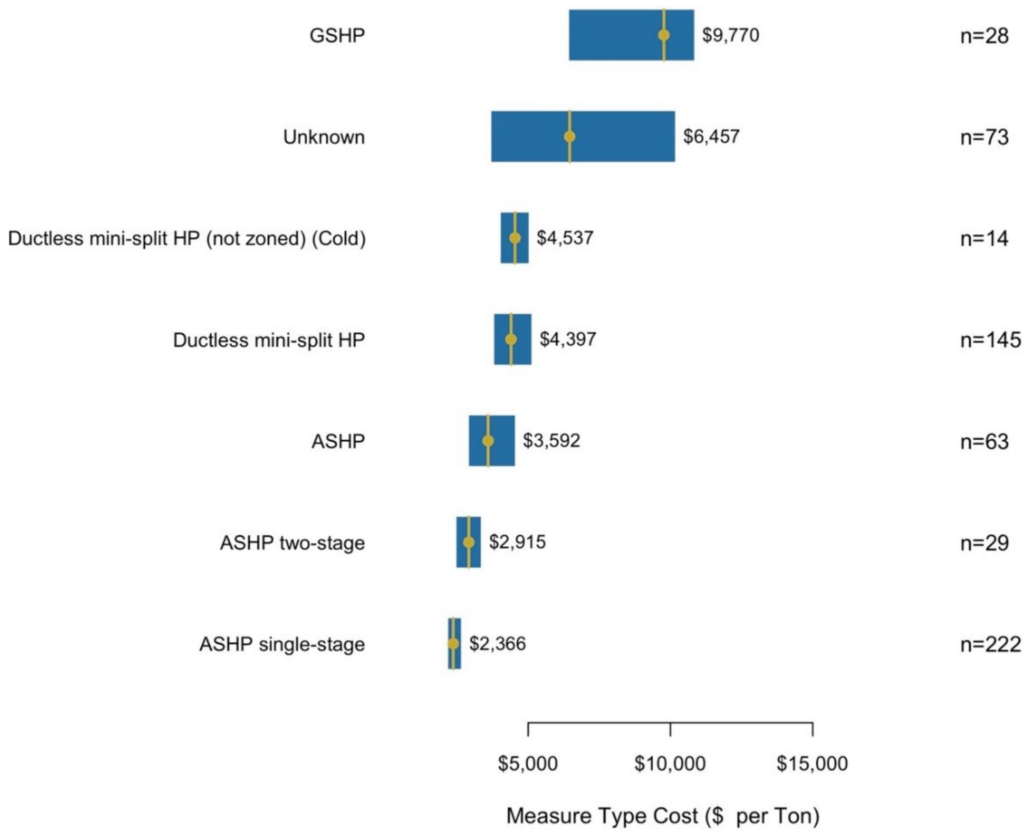


Figure G 16. Heat pump installation costs per ton.

We assessed how the cost of heat pump installations varied with system capacity (tons, Figure G 17), heating efficiency (HSPF, Figure G 18), cooling efficiency (SEER, Figure G 19 and Figure G 20) and cold climate status (Figure G 21).

Ductless heat pump costs most clearly varied with the system capacity, scaling in near-linear fashion from <1 ton up to 4.5 tons. The vast majority of systems were in the "0.5-1" ton up to the "4 to 4.5" ton range. Larger systems were so few that their distributions are unreliable for comparison. The system capacity normalized costs did not vary consistently with either the heating or cooling efficiency ratings (see Figure G 18 and Figure G 19). In fact, both efficiencies showed inverse relationships with cost in the most frequently reported efficiency categories, from 9-14 HSPF and from 17-22 SEER. These data appear to suggest that more efficient equipment had lower costs per ton. This is not the case in the marketplace, and we expect that these effects in the data set reflect the specifics of certain models/manufacturers of ductless heat pumps, along with when, where and by whom ductless these systems were installed. Based on the literature review by (Less et al., 2021), enhanced ductless heat pump efficiency (e.g., going from SEER 16 to 18) has a per ton cost range of $239 - $689. Across a sample of installations, unit efficiency does not appear to be a strong driver of installed cost.

Cold climate ductless heat pump models showed a median price premium of $192 per ton over standard units (see Figure G 21), though it is important to know that many systems in the 'Standard' category may have been cold climate models that were not adequately labeled in our data sources. The price premium for cold climate models based on the literature review was $100 - $400 per ton.

Figure G 17. Ductless heat pump installation costs by system capacity (tons).

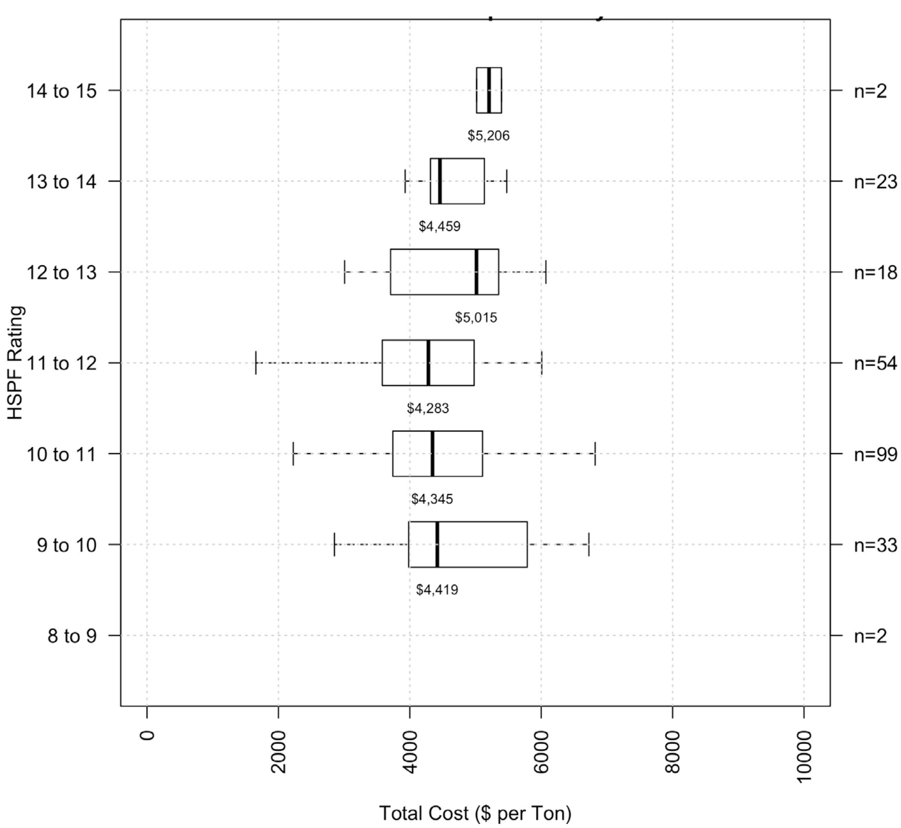


Figure G 18. Ductless heat pump costs by heating efficiency (HSPF)

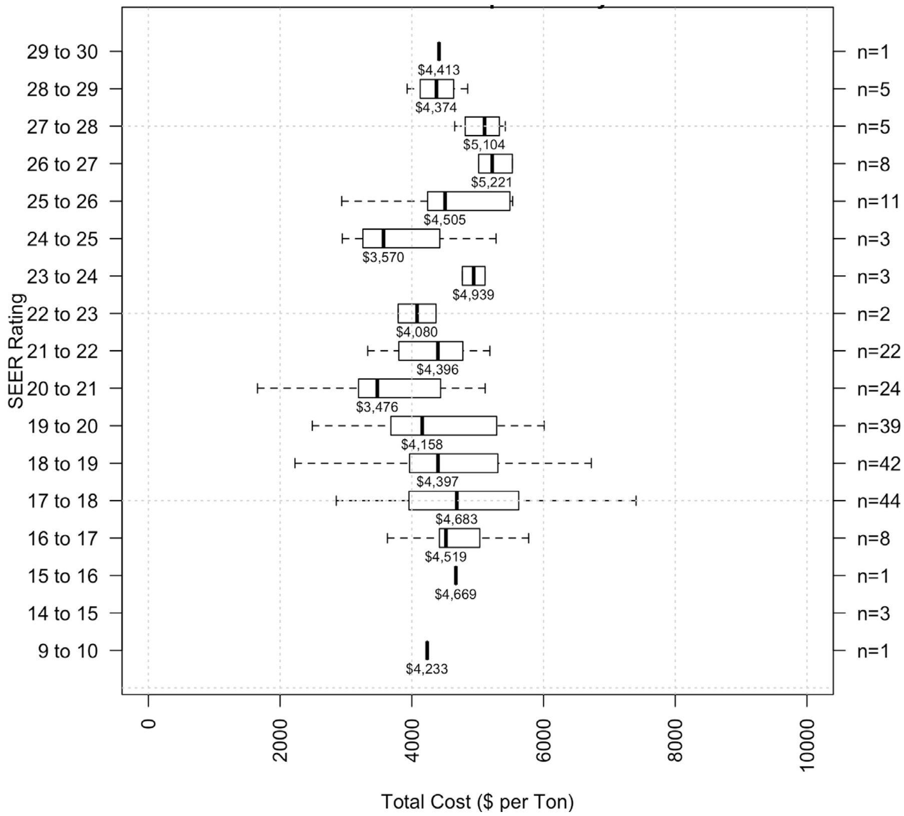


Figure G 19. Ductless heat pump costs by cooling efficiency (SEER).

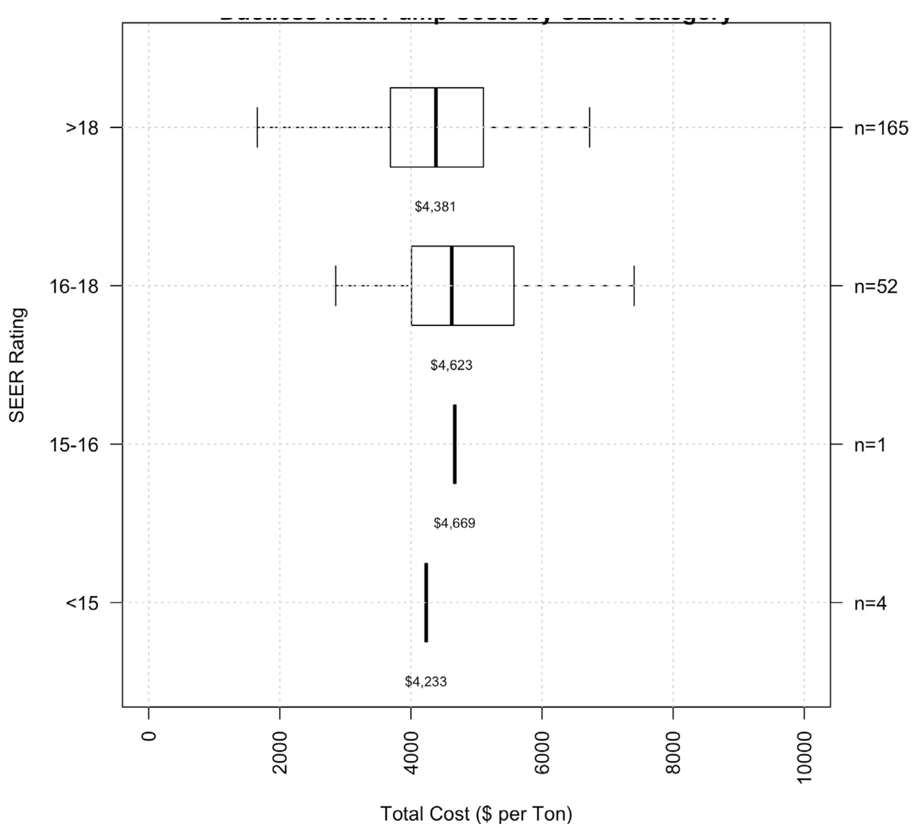


Figure G 20. Ductless heat pump costs by cooling efficiency (SEER) rating category.

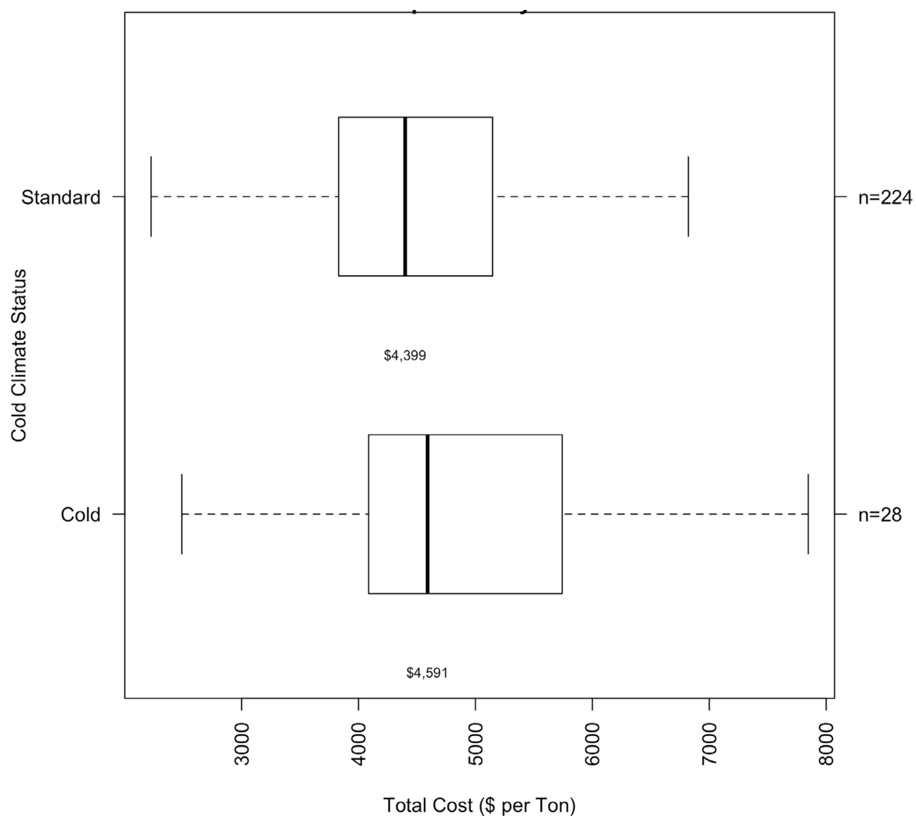


Figure G 21. Ductless heat pump costs by cold climate status.

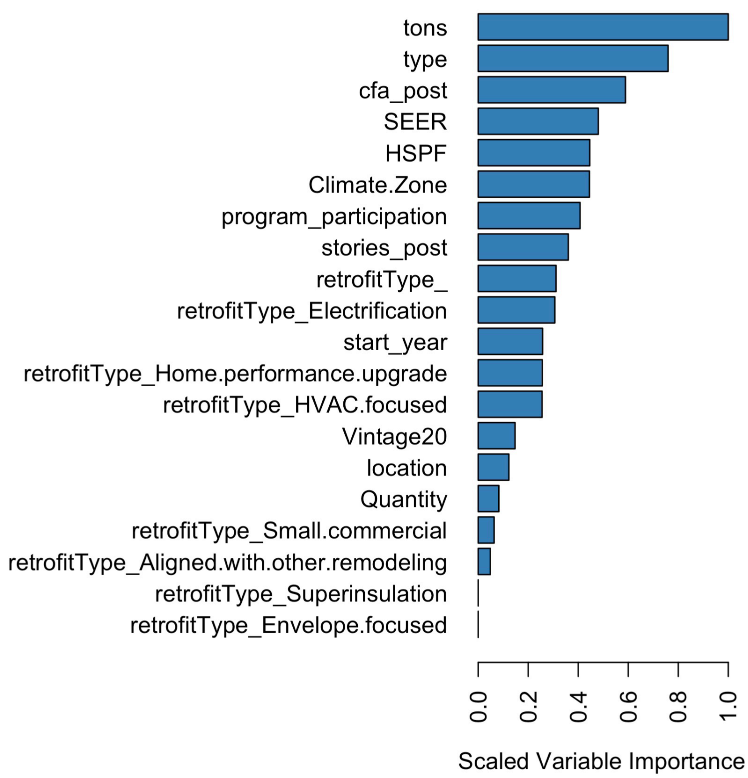


Figure G 22. Heat pump variable importance from random forest regression model.

Random forest regression models to predict heat pump installation costs were built, and the most important variables in estimating cost are shown in Figure G 22. This analysis suggests that the most important variables in determining heat pump cost include the capacity of the system (tons), the heat pump type (e.g., ductless mini-split vs. single-stage split heat pump), the home's floor area (cfa_post), the cooling and heating efficiencies (SEER and HSFP), Climate Zone, the Program the project participated in (program_participation), and the number of stories (stories_post). Less important variables included the location of the unit (location), the home vintage (vintage20), etc.

G.7.2 Heating

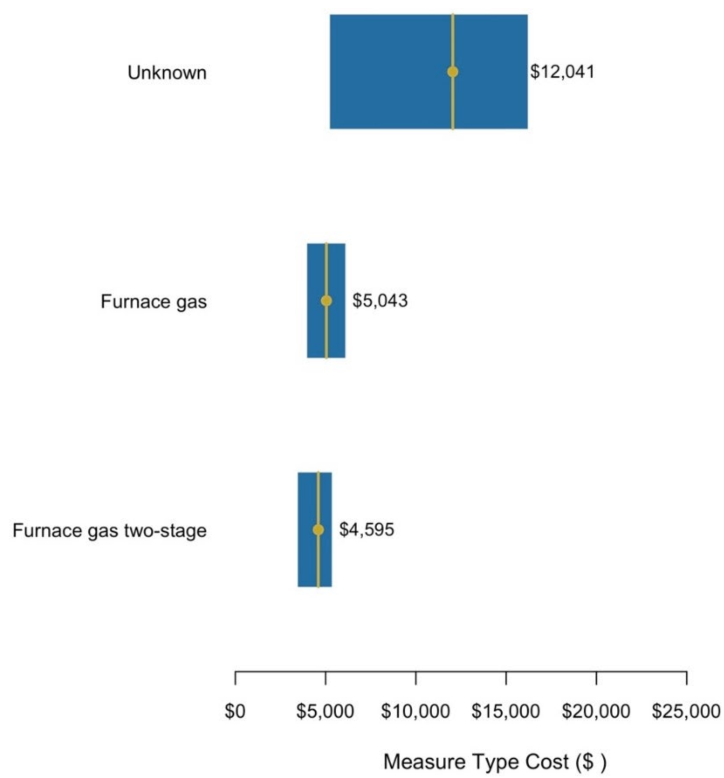


Figure G 23. Heating system installation costs.

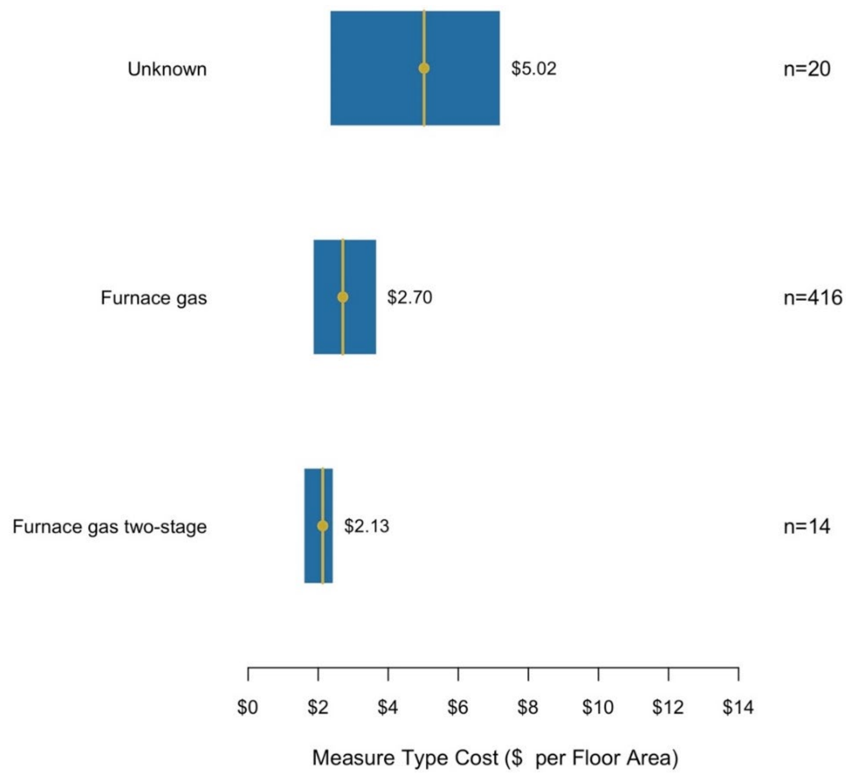


Figure G 24. Heating system installation costs by dwelling floor area.

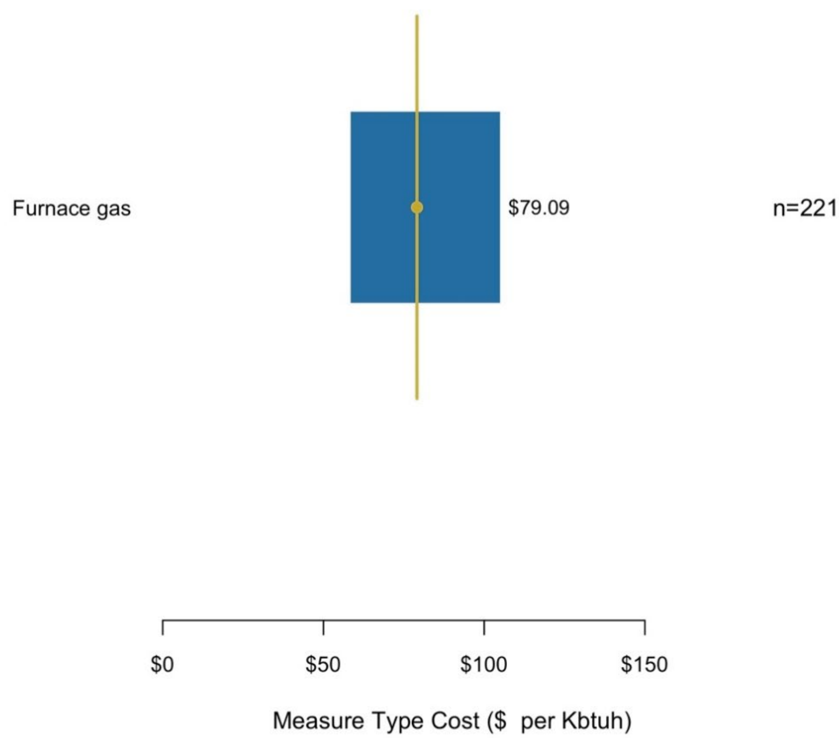


Figure G 25. Heating system installation costs per kBtu/hr. capacity.

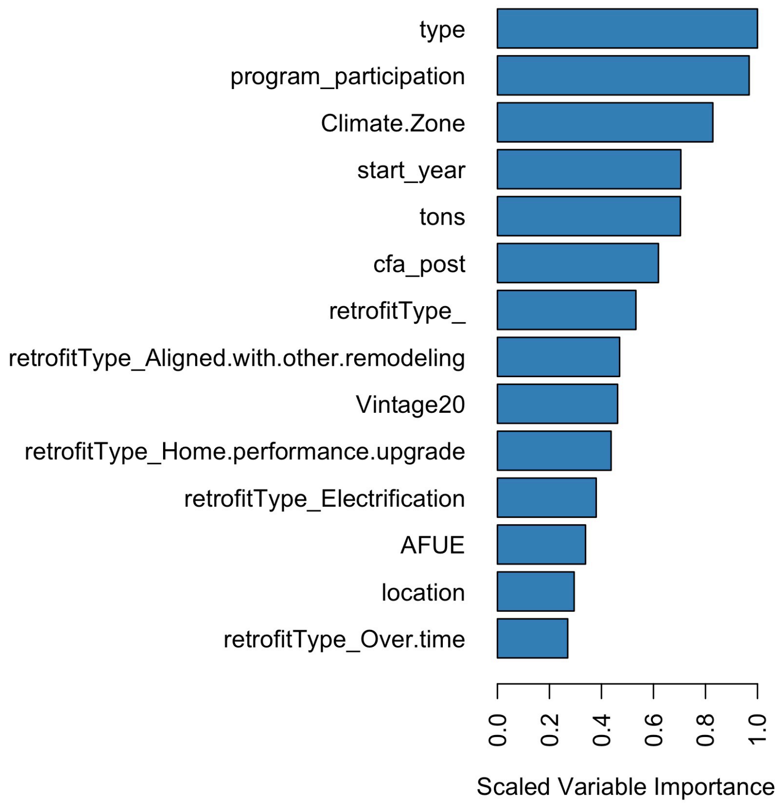


Figure G 26. Heating system variable importance from random forest regression model.

G.7.3 Cooling

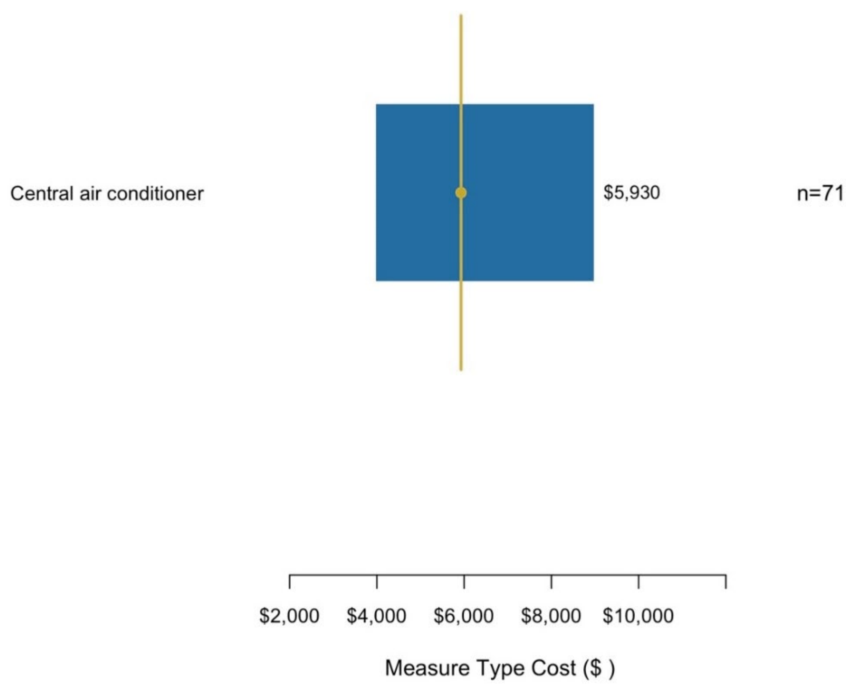


Figure G 27. Cooling system installation costs.

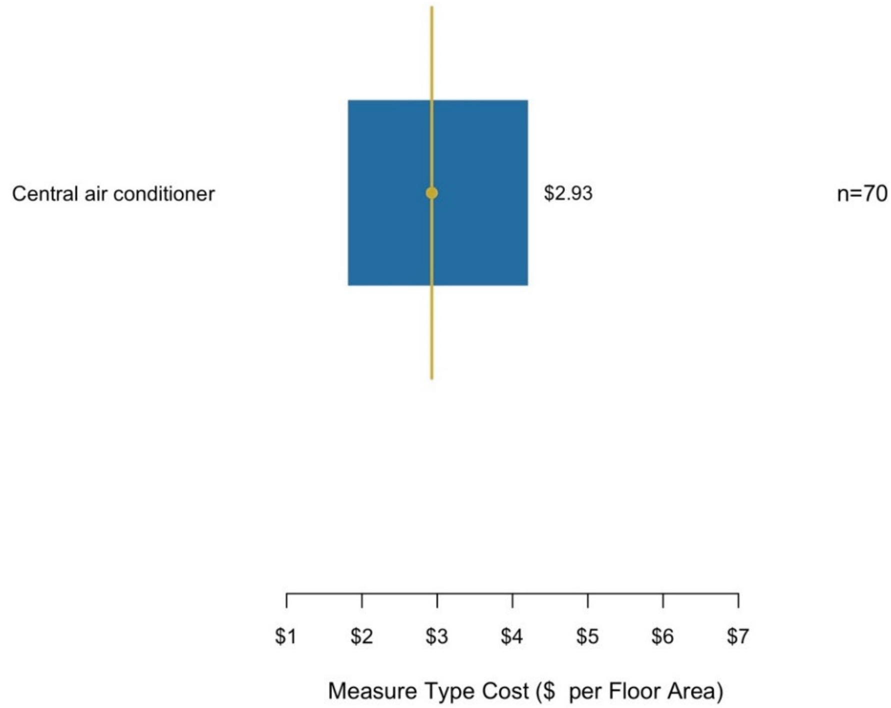


Figure G 28. Cooling system installation costs per dwelling floor area.

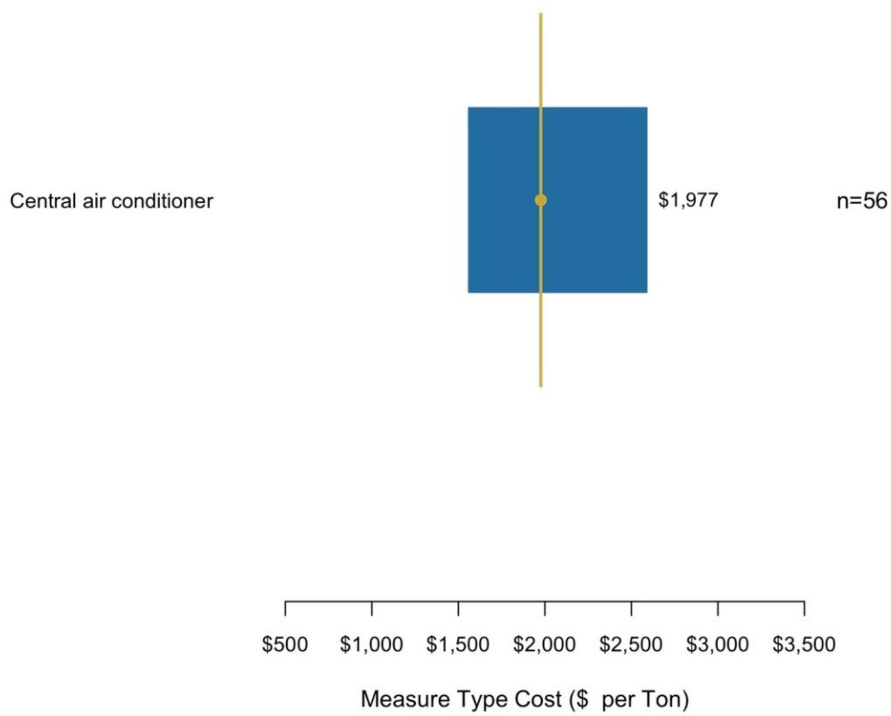


Figure G 29. Cooling system installation costs per ton.

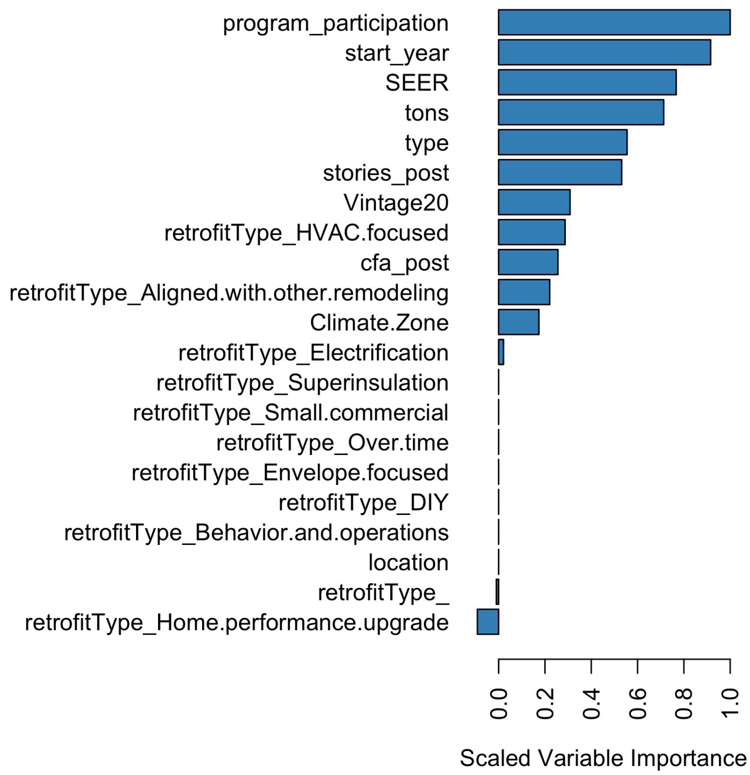


Figure G 30. Cooling system variable importance from random forest regression model.

G.7.4 Ducts

Over 200 duct system replacement and over 300 duct sealing measures were recorded in the database. Most of these had unspecified material types, while a small subset was clearly insulated flex duct. Across the recorded duct types, system replacement median costs were consistently between $3,645 and $3,953. Duct air sealing costs were typically much lower (median costs of $789). Duct sealing costs were remarkably stable across levels of leakage reduction, with median costs unwavering between 10-80% leakage reduction. Duct sealing cost distributions are shown by leakage reduction percentage in Figure G 33 (see Figure G 34 for floor area normalized costs). Some very slight increases in sealing costs are evident on the floor area normalized plot, where going from 30 to 70% duct leakage reductions increases costs by roughly $0.10 per ft^2. This suggests that most duct sealing work is bid on a fixed-price approach, and either some contractors are much more effective at reducing duct leaks for a given cost, or some houses simply have greater potential for reduction.

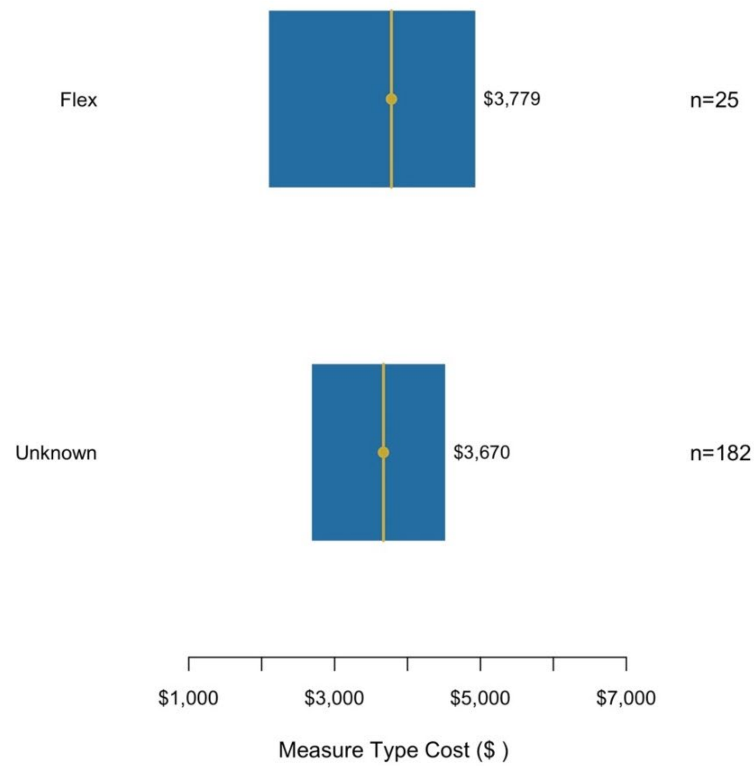


Figure G 31. Duct installation costs.

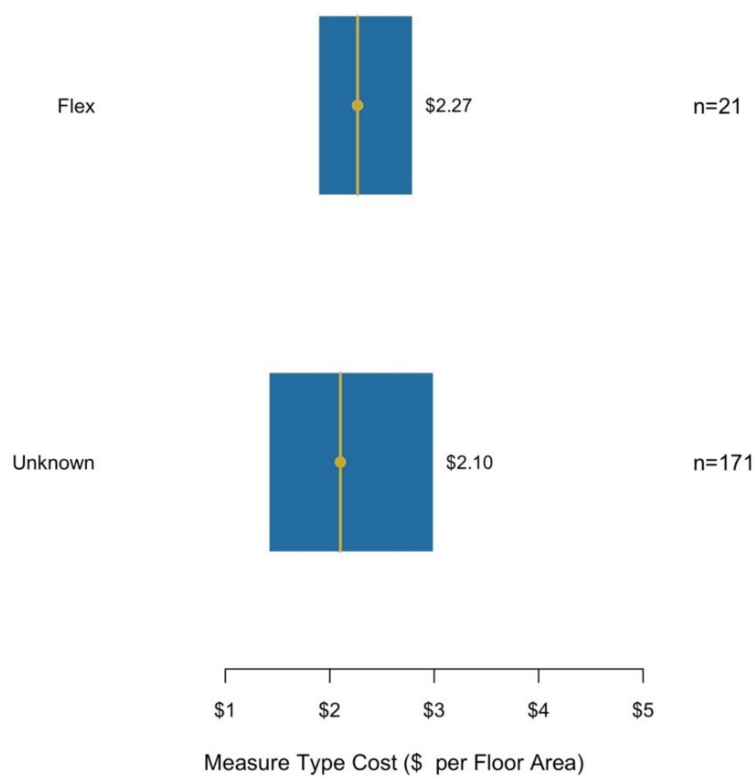


Figure G 32. Duct installation costs per dwelling floor area.

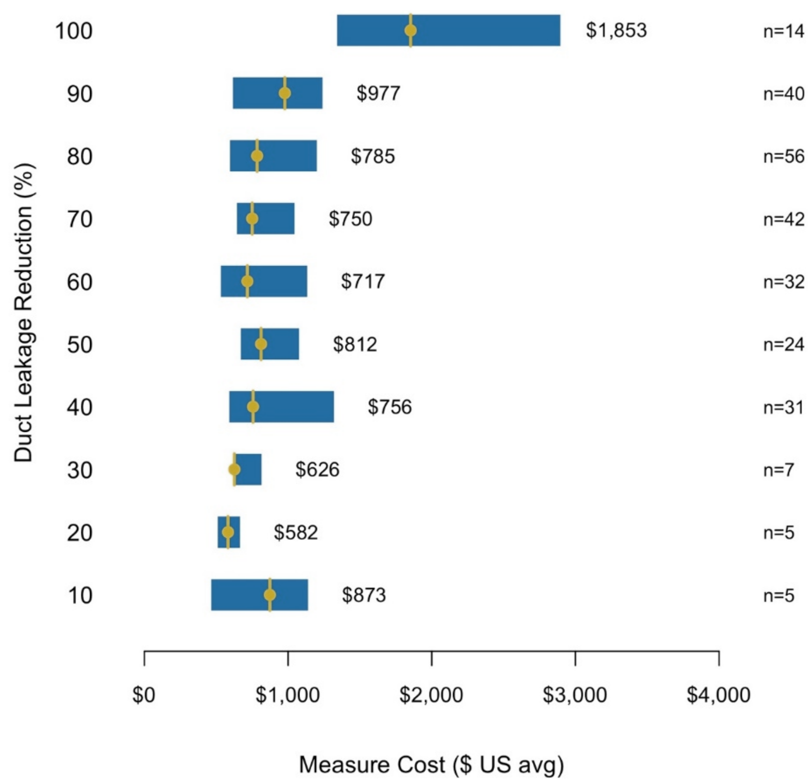


Figure G 33. Duct sealing measure costs by leakage reduction percentage.

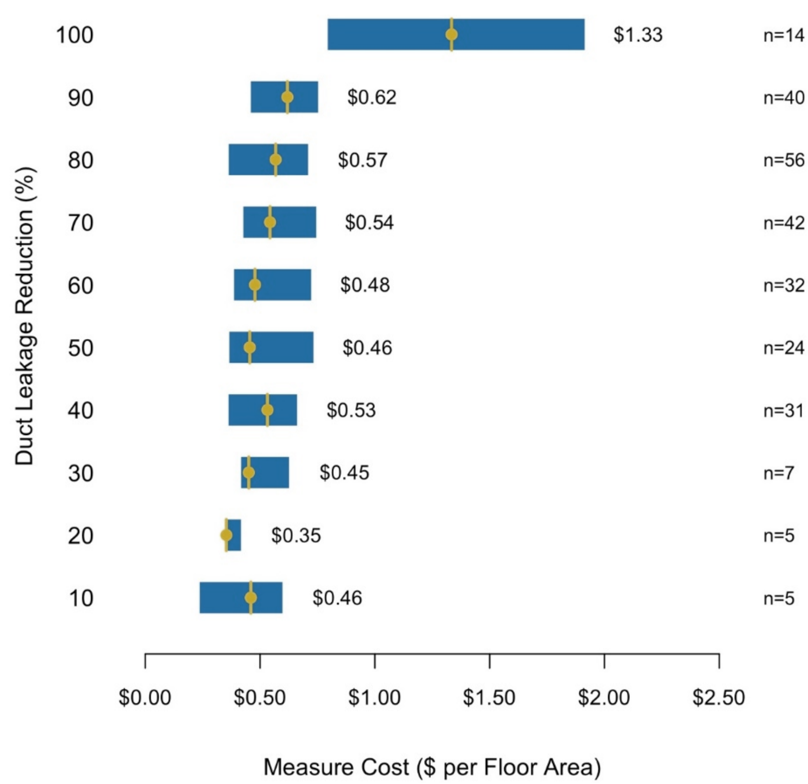


Figure G 34. Duct sealing measure costs by dwelling floor area by leakage reduction percentage.

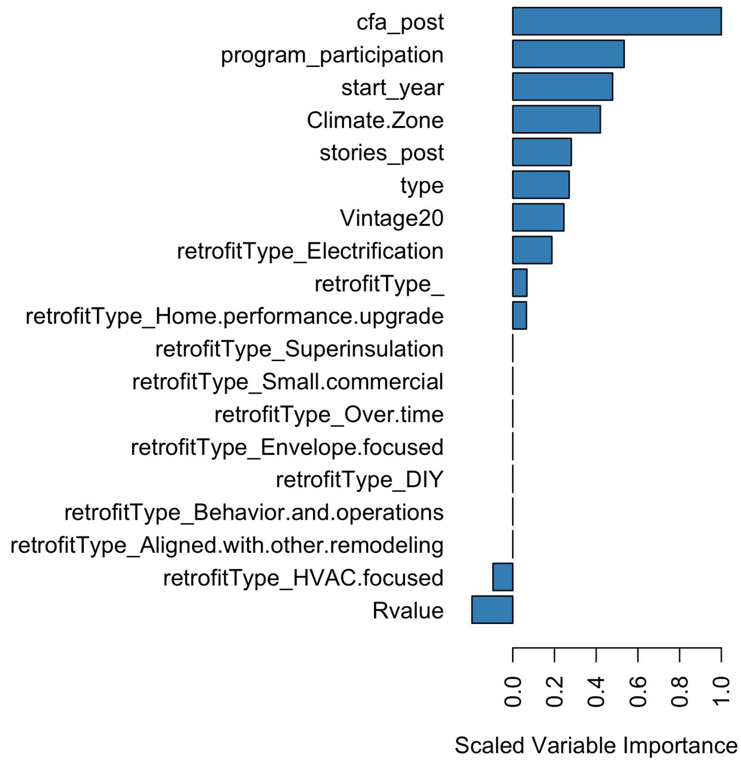


Figure G 35. HVAC Duct installation variable importance from random forest regression model.

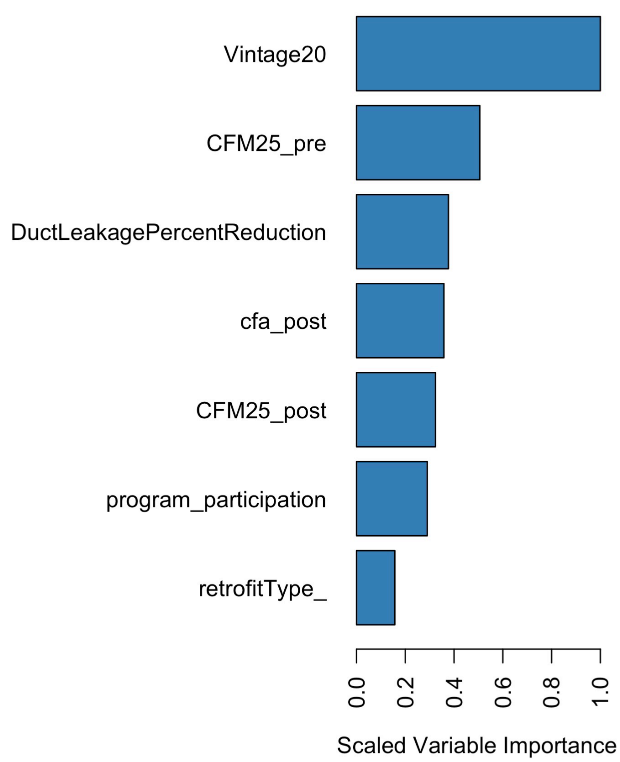


Figure G 36. Duct air sealing variable importance from random forest regression model.

G.7.5 Ventilation

Mechanical ventilation is a critical element of energy retrofits that reduce air leakage. The ASHRAE 62.2 ventilation standard has built-in approaches for determining when a mechanical system is necessary, based on background envelope leakage rates, climate and building characteristics. Nevertheless, installation of mechanical ventilation was infrequent in this database, with only 71 installations recorded in over 1,700 projects. These were roughly split between low-cost exhaust fan units and higher-cost units with heat recovery (both ERV and HRV). Overall, installation of mechanical ventilation added $733 to a project. When disaggregated by ventilation fan type, the costs varied substantially. Exhaust fan median costs were $748 (combination of Dwelling exhaust and Local exhaust in Figure G 37), while heat recovery unit median costs were $2,835 (combination of Dwelling HRV and Dwelling ERV below). The most important factors in determining the cost of mechanical ventilation installation were the ventilation system type, the program the project participated in, and the climate zone (see Figure G 38).

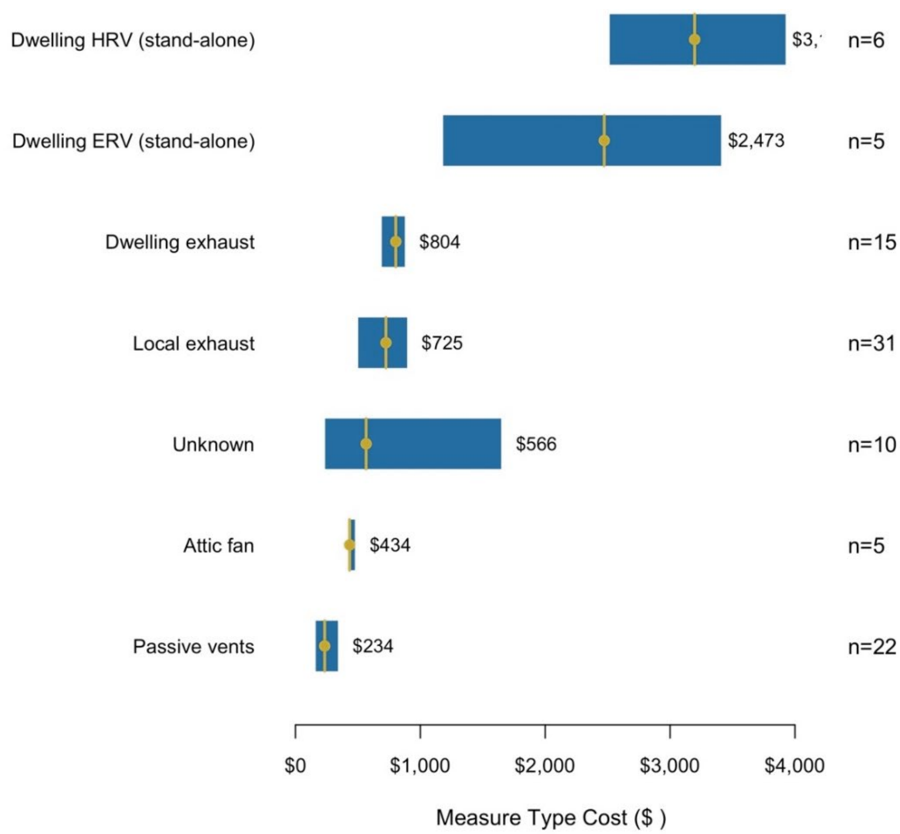


Figure G 37. Ventilation system installation costs.

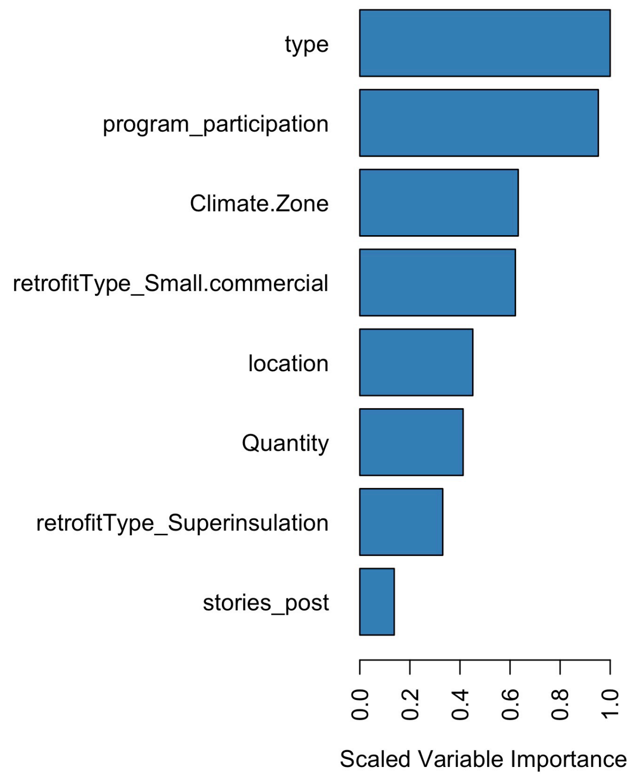


Figure G 38. Mechanical ventilation variable importance from random forest regression model.

G.8 Attic

The attic section was the third most frequently recorded in the database (after HVAC and House), with 1,061 recorded measures with costs, totaling $2.71 million (2019 $USD). Attic measure total costs are summarized in Figure G 39, and the costs are summarized by dwelling floor area and surface treatment area in Figure G 40 and Figure G 41. By far the most frequently reported attic measure was insulation of the framed floor surface, followed by attic rebates and roof insulation. In addition to these components, the knee wall and exterior finishes are all addressed in subsections below.

The materials used and the surface being insulated had substantial impacts on the attic measure costs. For example, blown cellulose insulation was a low-cost means to insulate the attic framed floor, with median normalized costs of $1.91 per ft^2 at a median R-value of 44. In contrast, the most frequently reported method of insulating the roof surface was with R-35 closed cell spray foam insulation, at $8.32 per ft^2. Debates are ongoing as to the relative merits of fibrous vs foam insulation materials, as well as placement of insulation at the attic framed floor vs. the roof. In this dataset, less R-value was achieved with closed cell foam, at more than quadruple the price per ft^2, and sloped roof insulation requires greater surface area than framed floor approaches. When other design goals allow, framed floor blown insulation is the most cost-effective approach to attic retrofit.

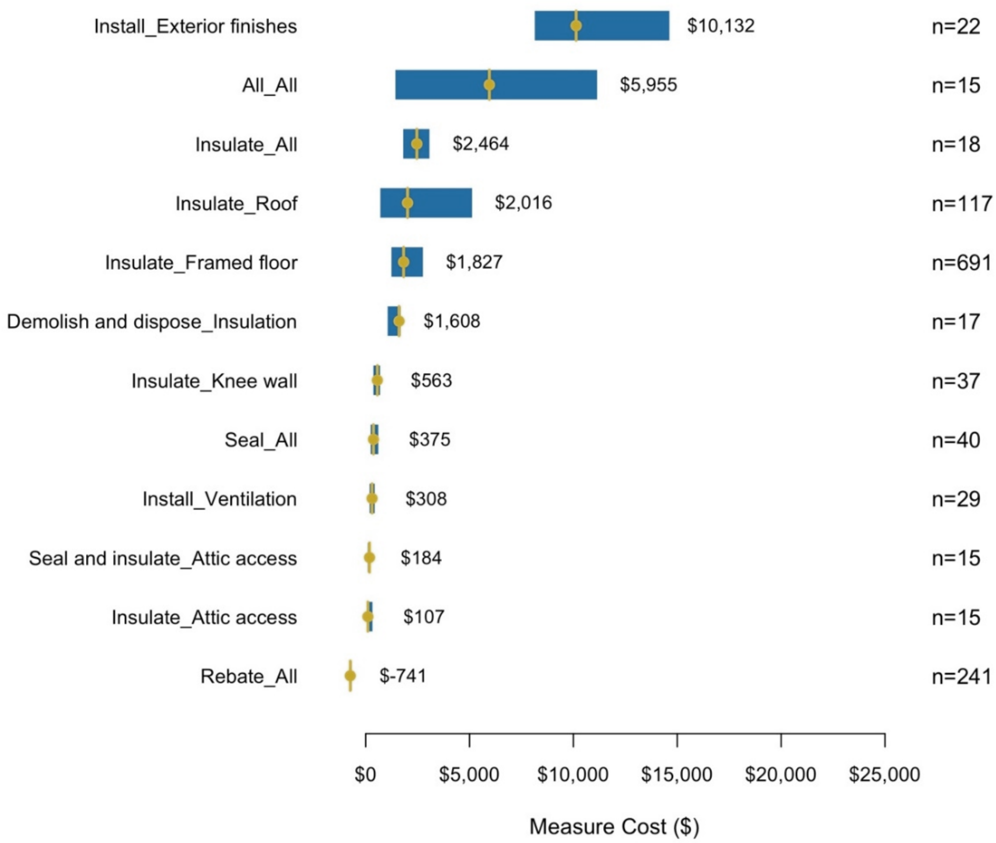


Figure G 39. Attic measure costs.

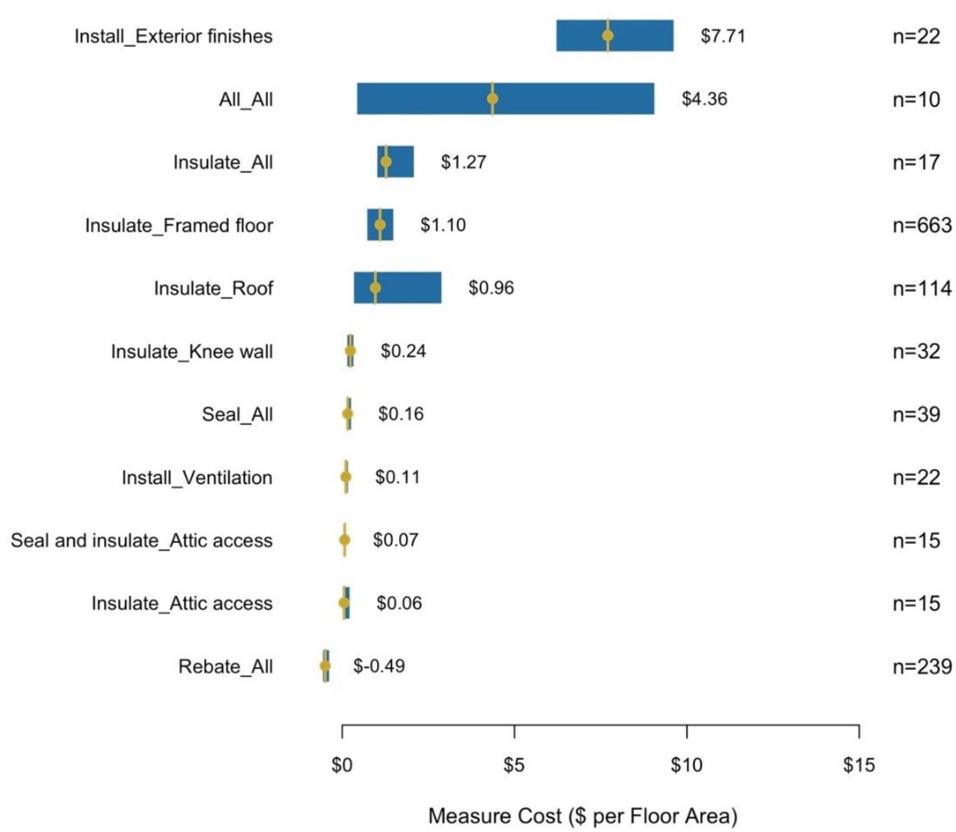


Figure G 40. Attic measure costs per dwelling floor area.

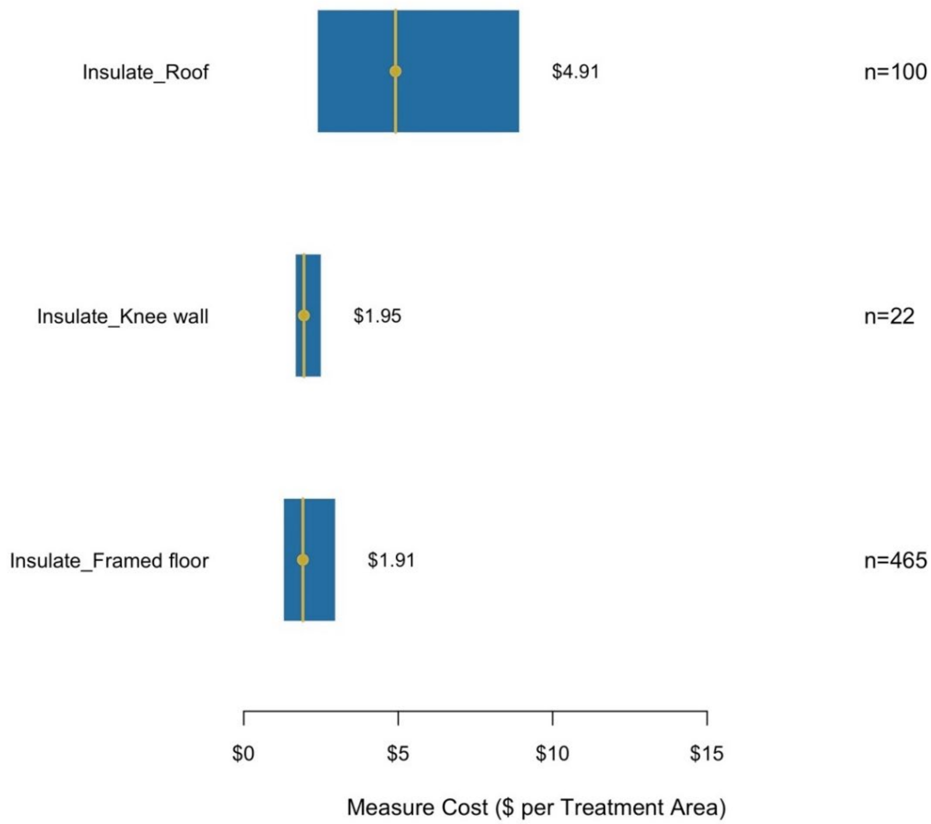


Figure G 41. Attic measure costs per treatment area.

G.8.1 Framed Floor

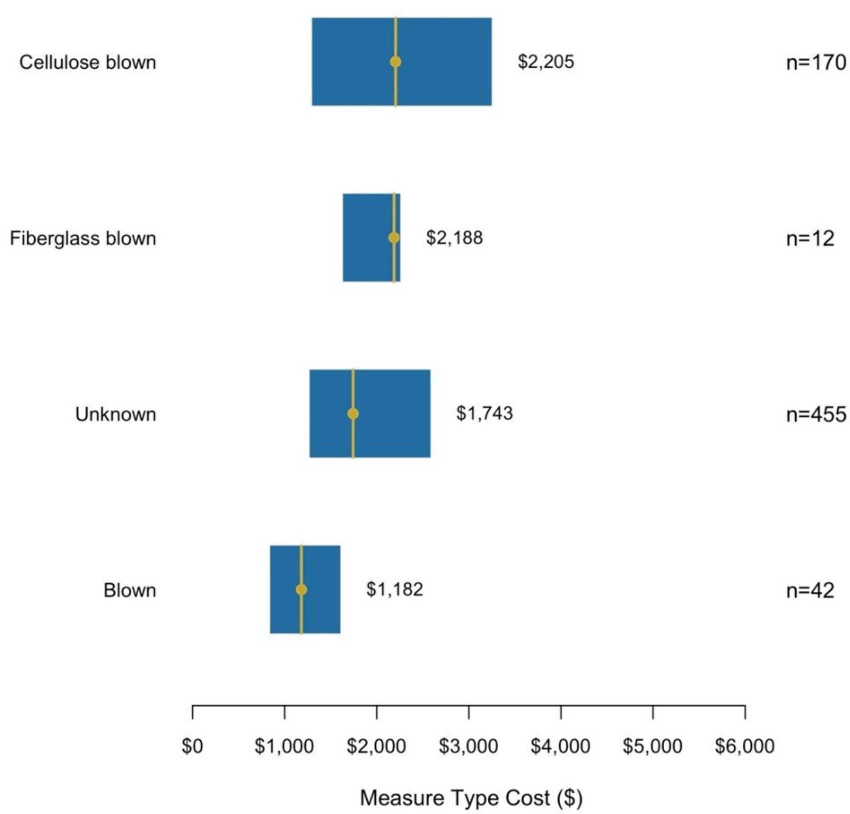


Figure G 42. Attic framed floor insulation costs.

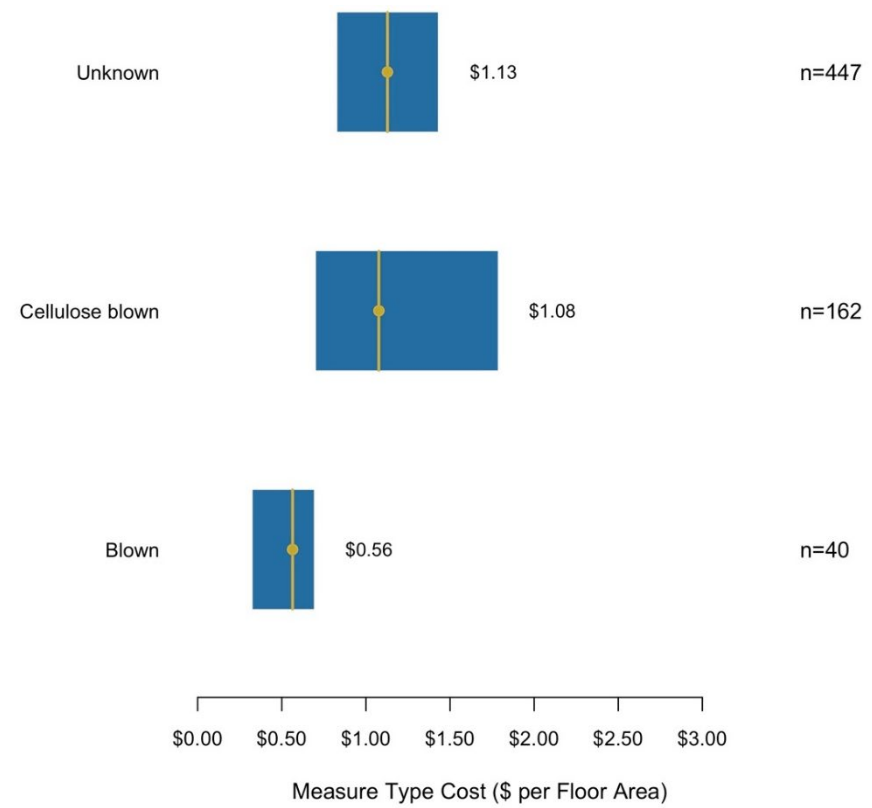


Figure G 43. Attic framed floor insulation costs per dwelling floor area.

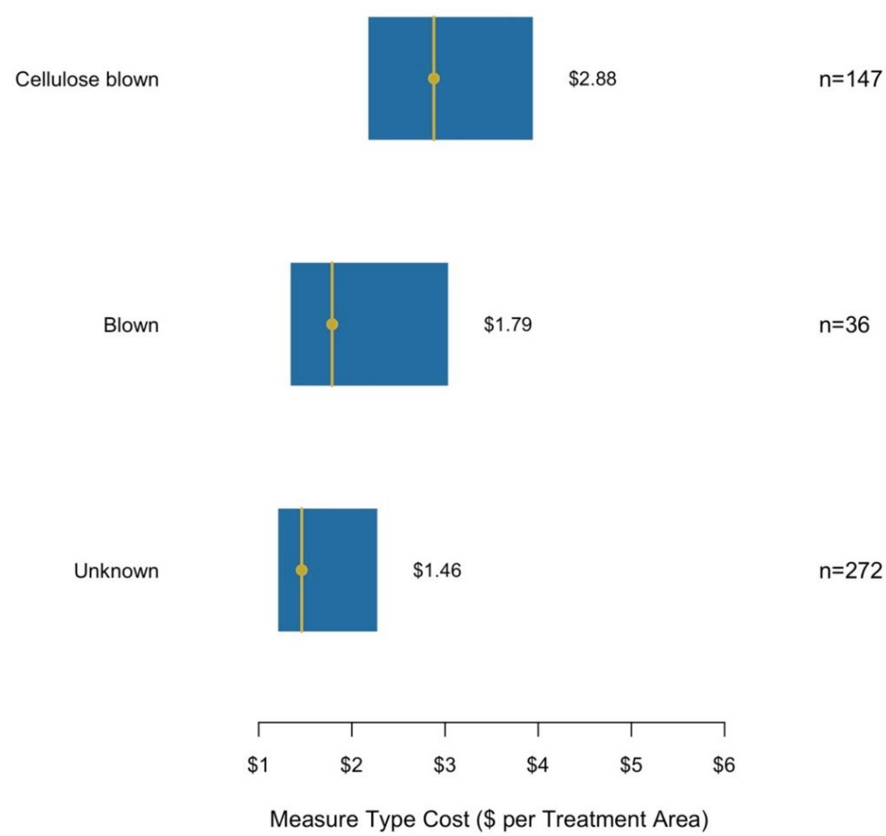


Figure G 44. Attic framed floor insulation by treatment area.

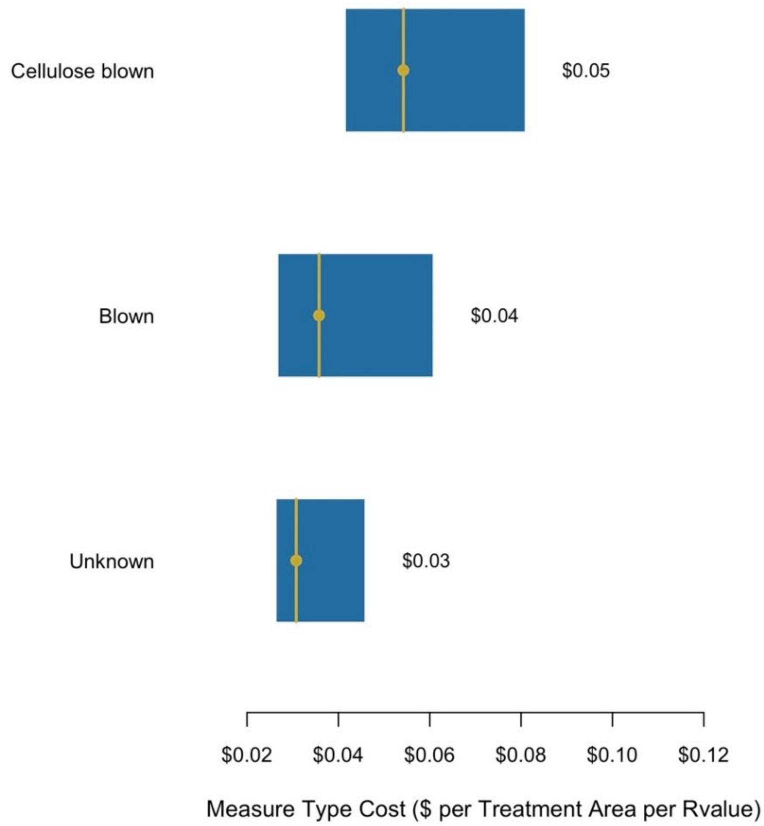


Figure G 45. Attic framed floor insulation by treatment area per R-value.

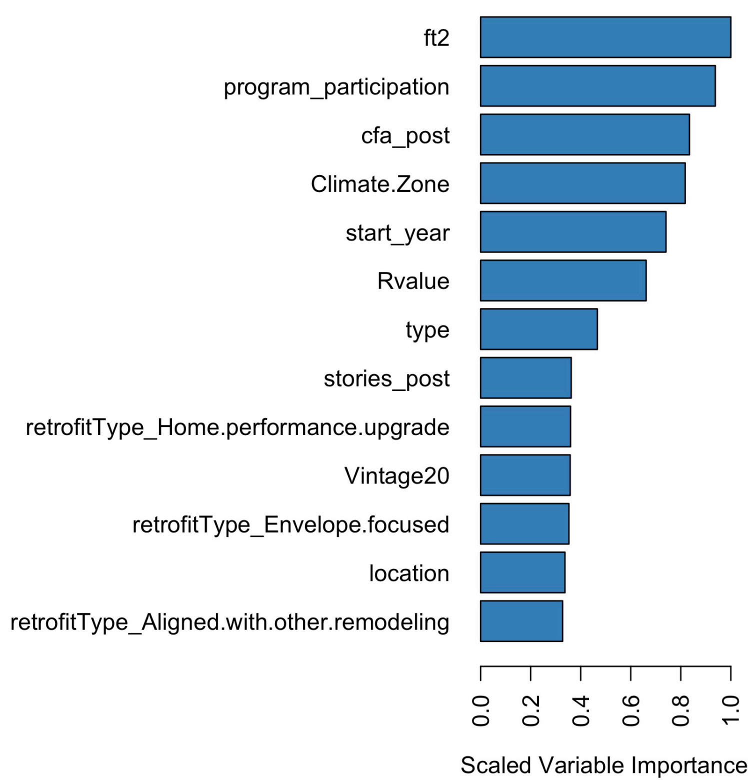


Figure G 46. Attic framed floor insulation variable importance from random forest regression model.

G.8.2 Roof

Roof deck insulation measure costs are shown per project (Figure G 47) and per treatment area (Figure G 48). Similar roof insulation upgrades were summarized from the research literature by (Less et al., 2021). The following high-level summary is reproduced from that report.

- Attic floor: \$2.37 - \$16.00 per ft^2
- Below roof deck: \$6.24 - \$18.39 per ft^2
- Above roof deck: \$10.05 - \$22.22 per ft^2

Comparable values in the upgrades database varied by material type, ranging from \$8.32 per ft^2 for closed cell spray foam down to \$6.40 per ft^2 for cellulose insulation. These are consistent with the lower bounds of the values reported in the literature for insulation placed below the structural sheathing.

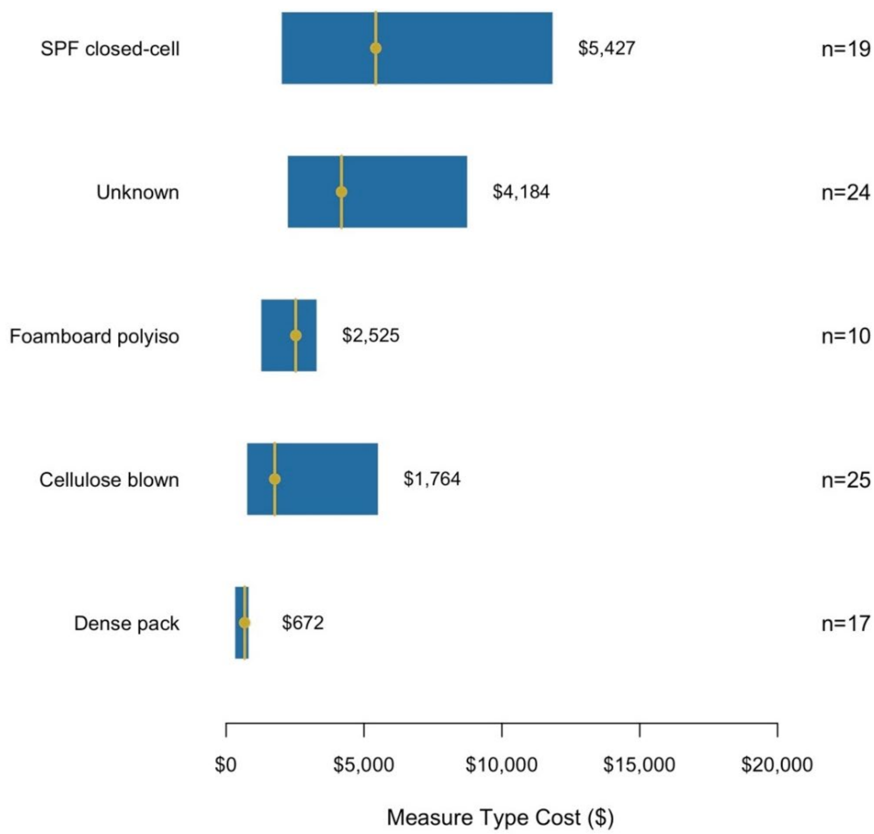


Figure G 47. Attic roof insulation costs.

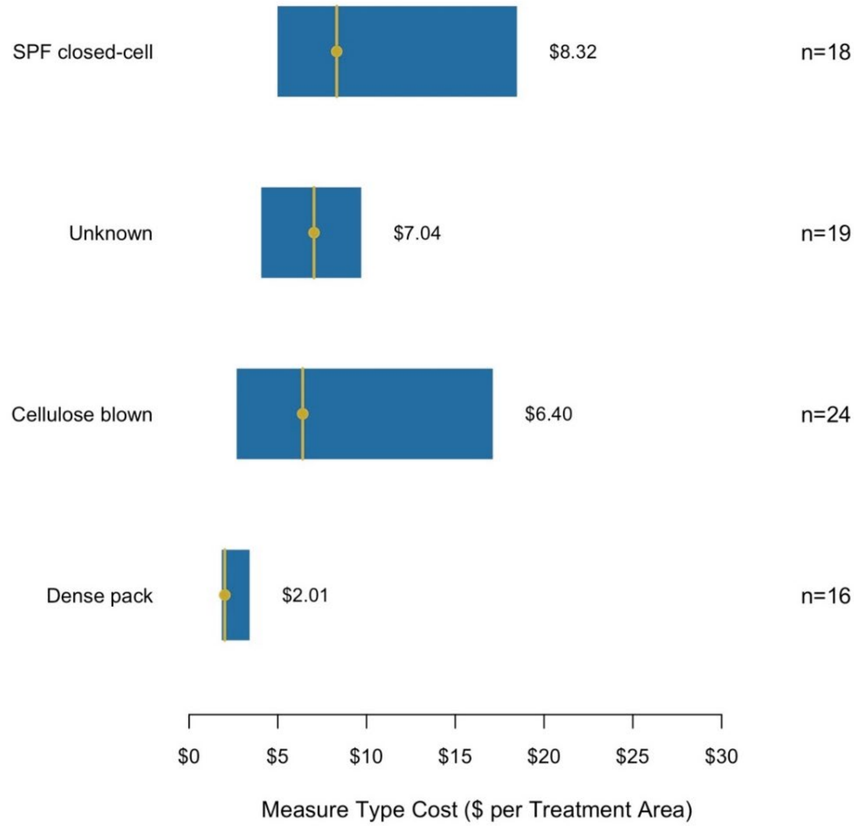


Figure G 48. Insulate roof insulation costs per treatment area.

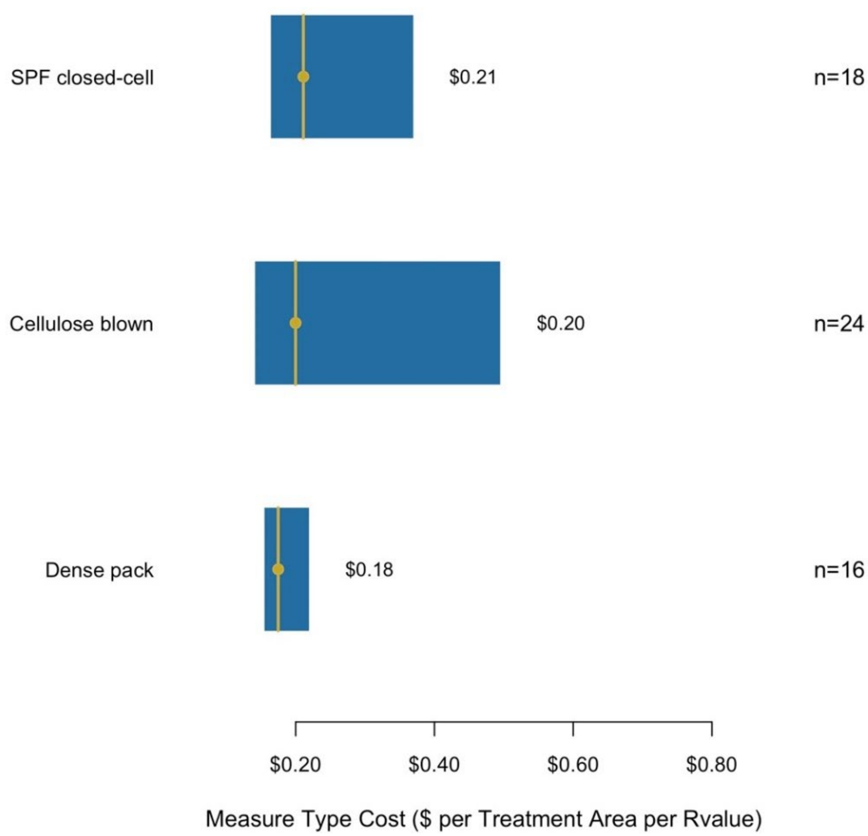


Figure G 49. Insulate roof insulation costs per treatment area per R-value

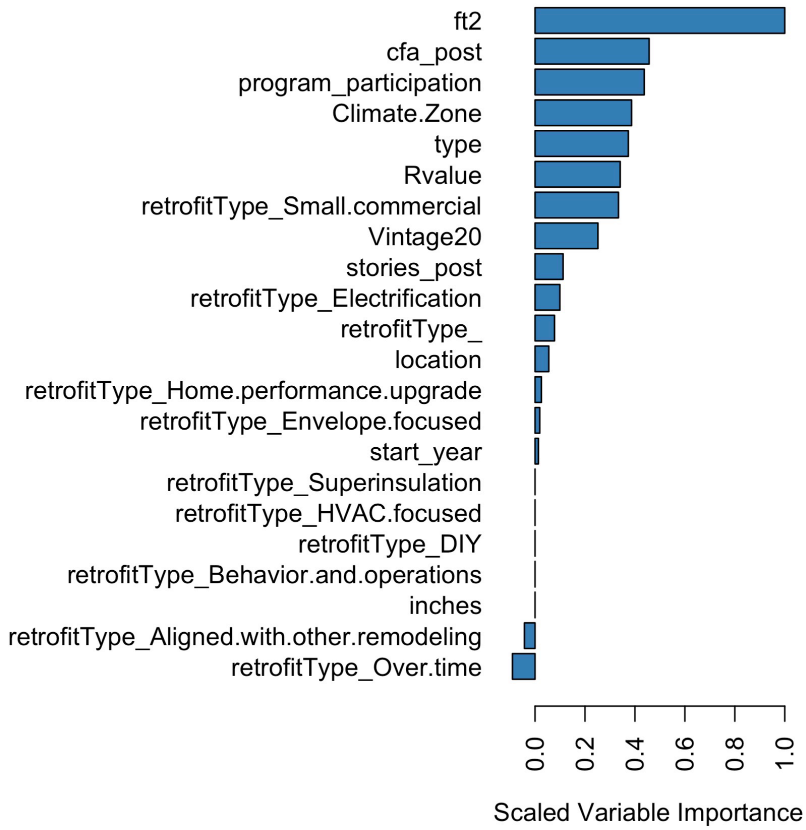


Figure G 50. Attic roof insulation variable importance from random forest regression model.

G.8.3 Knee Walls

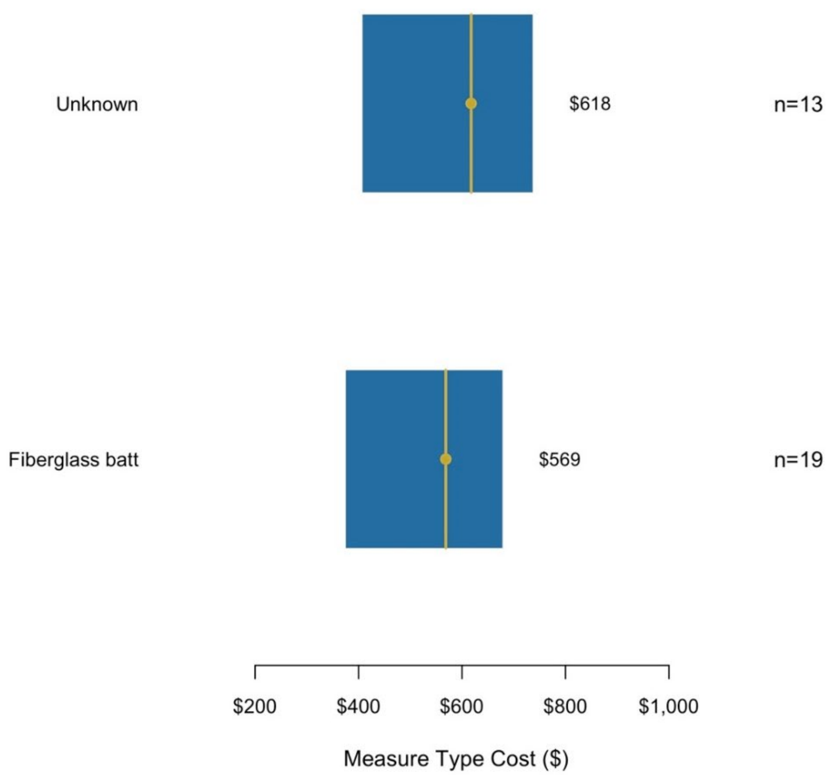


Figure G 51. Attic knee wall insulation costs.

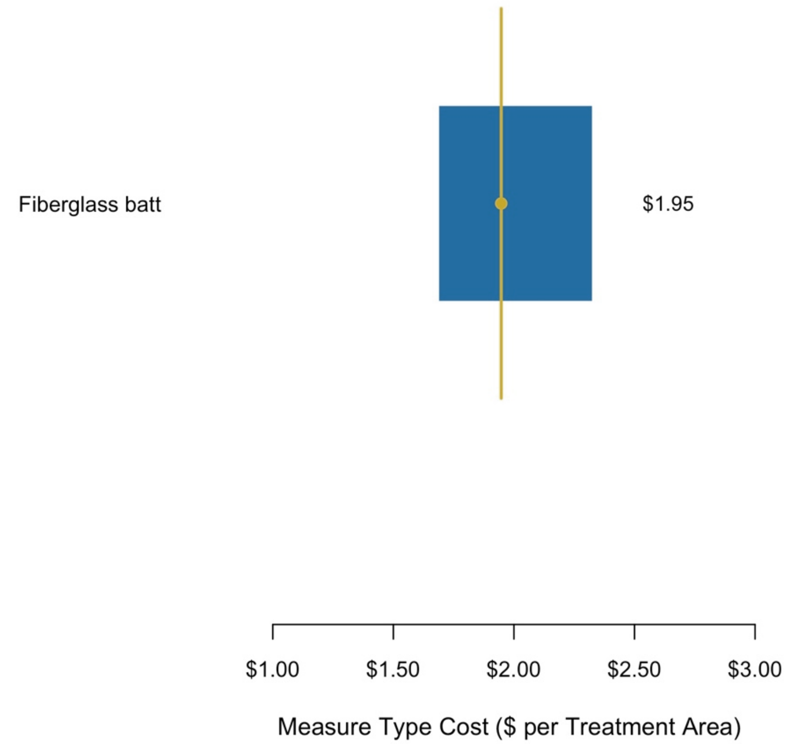


Figure G 52. Attic knee wall insulation costs per treatment area.

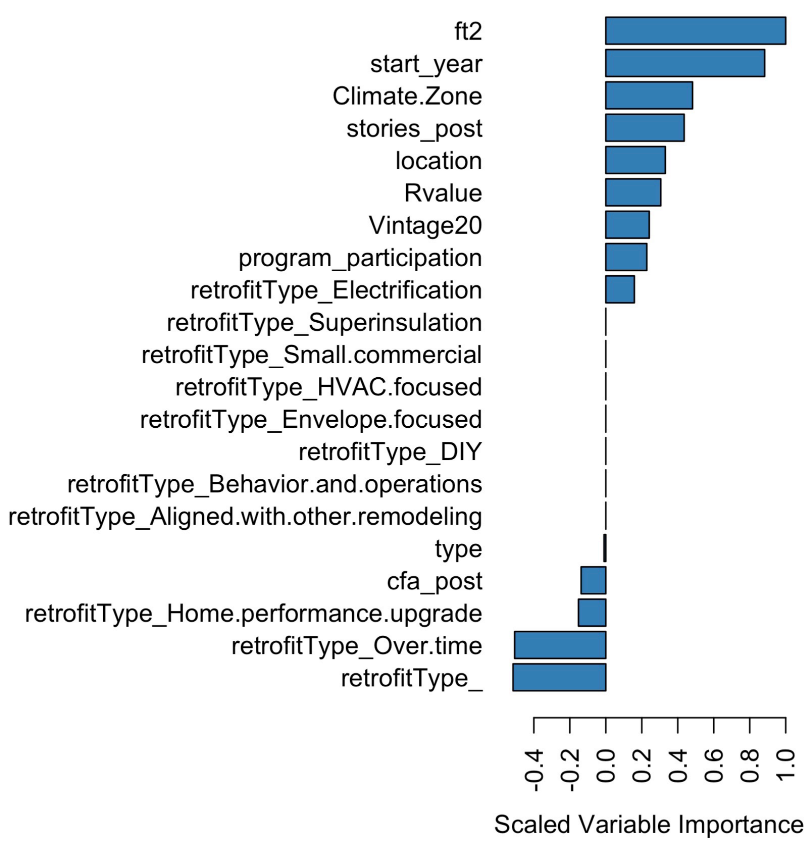


Figure G 53. Attic knee wall insulation variable importance from random forest regression model.

G.8.4 Exterior Finishes

Exterior finishes were not recorded frequently in the database – with only 17 reported measures. Figure G 54 summarizes the exterior finishing costs that were significant expenses in most cases.

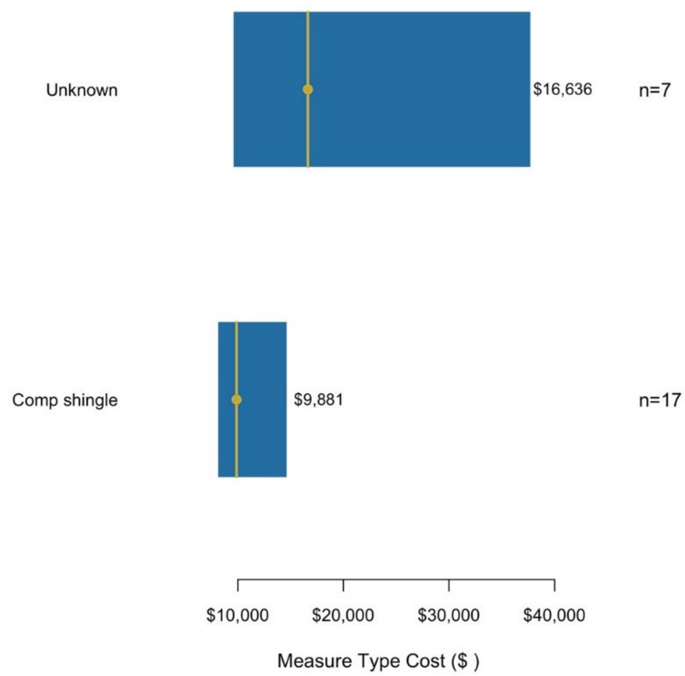


Figure G 54. Exterior finishes installation costs.

G.9 Walls

The wall section was the fifth most frequently recorded in the database, with 289 costed measures, totaling $1.1 million (2019 $USD). Wall measure total costs are summarized in Figure G 55. Effectively all retrofit measures with recorded costs in the wall section were for insulation, with some projects reporting rebates and a few projects reporting painting. Due to the dominance of wall insulation measure in this section, the total insulation costs by component type are shown in Figure G 56. Normalization by treatment area is shown in Figure G 57. The most frequent wall insulation type was Unknown, followed by dense packed (from inside or from outside) or blown cellulose insulation. The variable importance values from the random forest regression model for predicting wall insulation costs are shown in Figure G 59, and the most important variables in determining costs were the type of insulation, treatment area (ft^2), followed by program participation, location (cavity vs. exterior) and R-value.

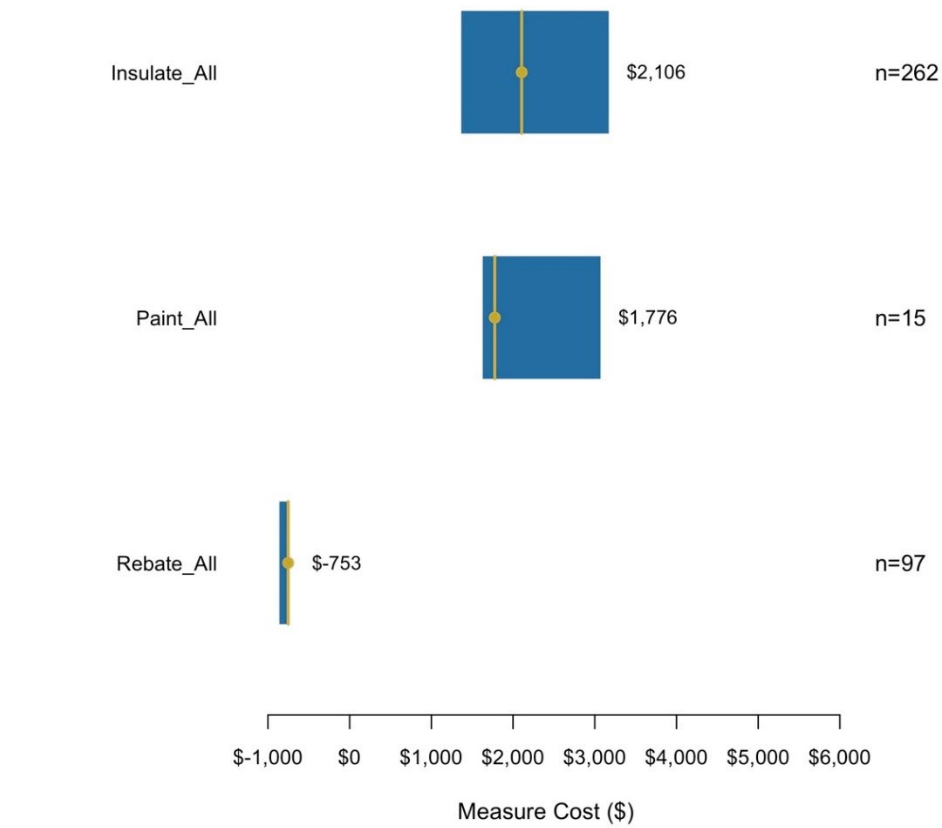


Figure G 55. Wall measure costs.

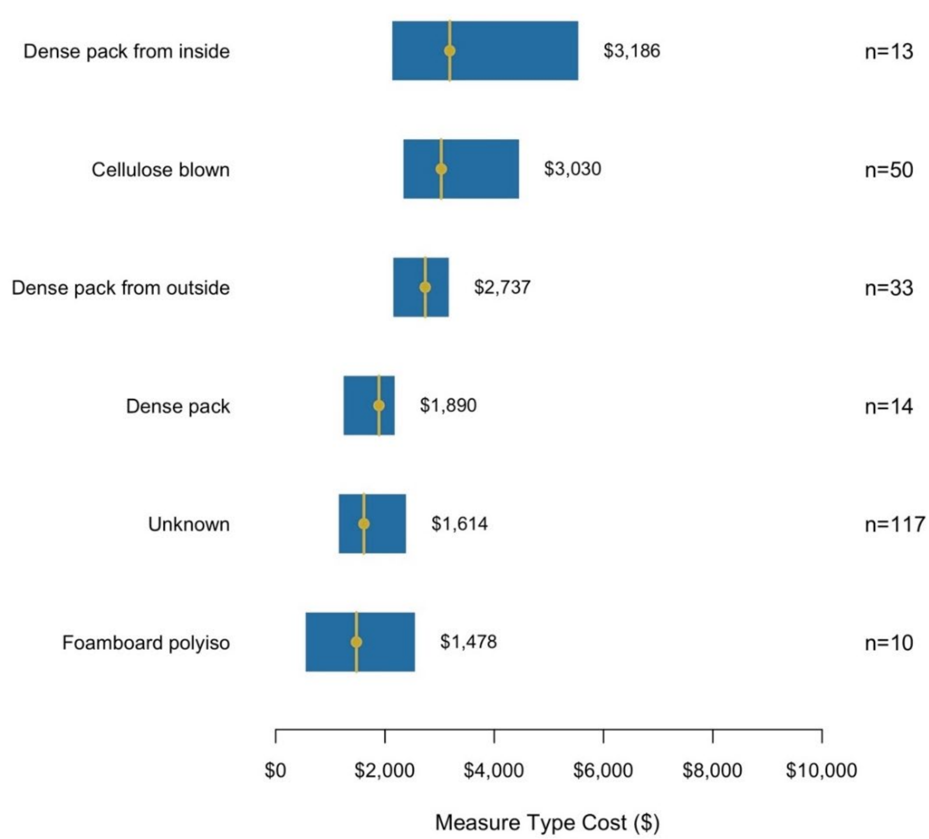


Figure G 56. Wall insulation costs.

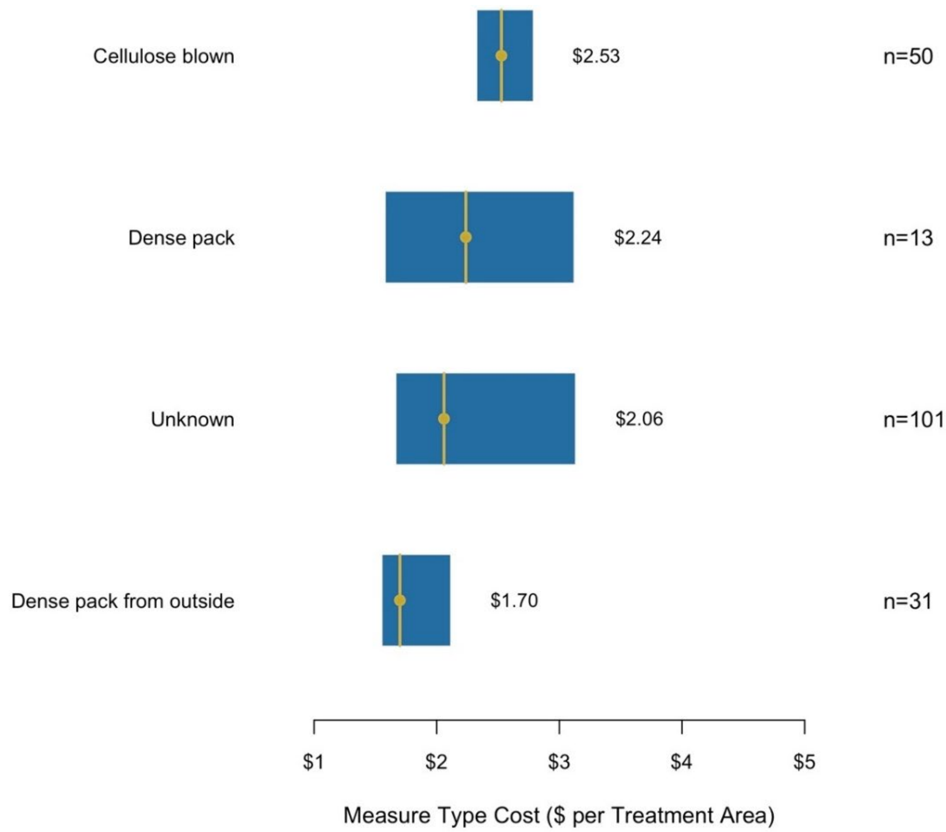


Figure G 57. Wall insulation costs per treatment area.

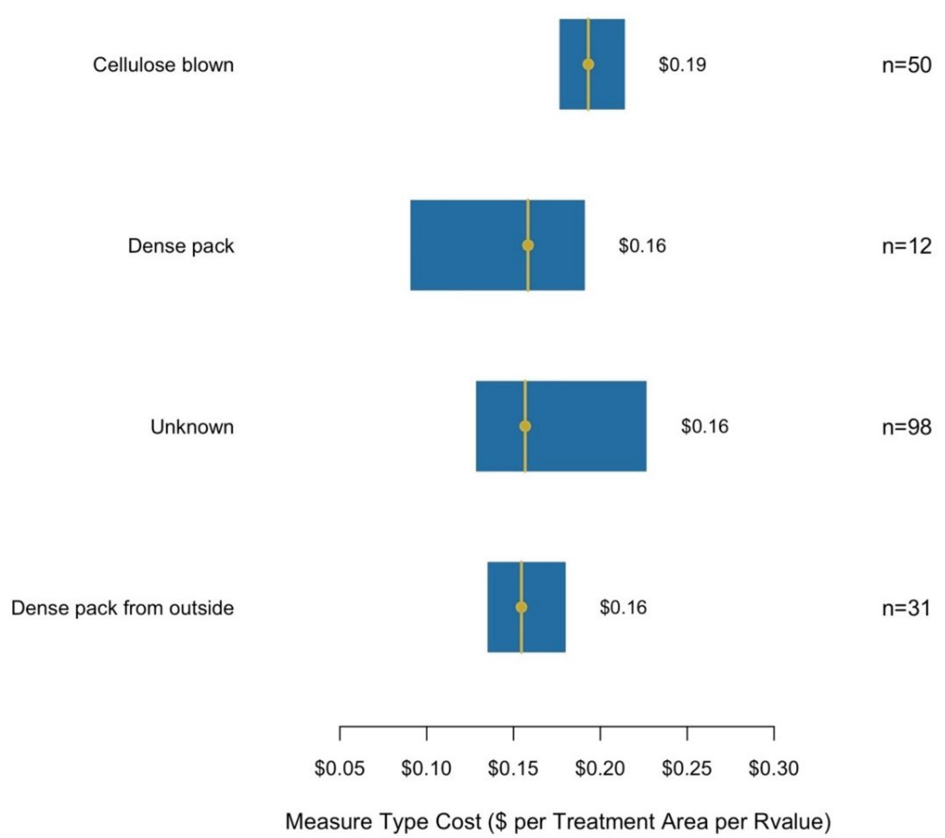


Figure G 58. Wall insulation costs per treatment area per R-value.

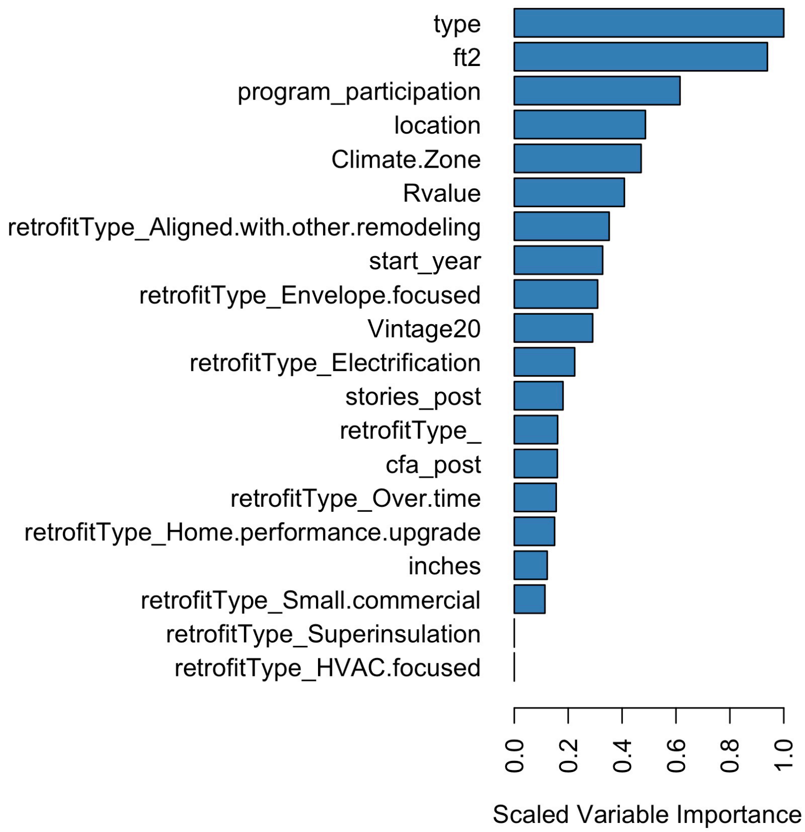


Figure G 59. Above grade wall insulation variable importance from random forest regression model.

Overall, very few projects included exterior wall insulation that would achieve R-values exceeding the typical R-11 to R-15 values in framed wall cavities. Of the 265 projects that reported wall insulation measures, only 15 included insulation on the exterior (5.7% of wall insulation projects). Of projects that included exterior wall insulation, very few of them recorded efforts to wrap the entire exterior of the dwelling in insulation. Rather, smaller wall sections were addressed on the order of hundreds of square feet. Based on the very few projects available (n=4), Figure G 60 shows the comparison of costs per treatment area for projects that included exterior wall insulation vs. those that only did cavity-fill. We see that exterior insulation was much more expensive (by roughly 4x), with a median cost of \$9.36 per ft^2 compared with \$2.24 per ft^2 for cavity fill projects.

(Less et al., 2021) reported on upgrade costs of adding exterior wall insulation to energy retrofit projects. The high-level summary is reproduced below.

- Exterior insulation without finish: \$4.94 - \$15.00 per ft^2
- Exterior insulation with finish: \$13.10 - \$23.05 per ft^2
- Exterior finish: \$6.10 - \$8.50 per ft^2

The lowest achievable cost for adding exterior wall insulation in the literature was in the range of \$5 - 7 per ft^2, as many of these prices were derived from projects where concerted R&D efforts were being made to identify the lowest cost approaches to insulating the exterior of walls (e.g., EIFS). Typical costs were higher (\$9.36 per ft^2) in the few database projects that were submitted, while the range (roughly \$5-13 per ft^2) is consistent with the literature values. These marginal costs might be justifiable in some cases where the exterior cladding is already being removed and replaced. If not aligned with this work, total upgrade costs for exterior insulation and cladding replacement were typically >\$15 per ft^2.

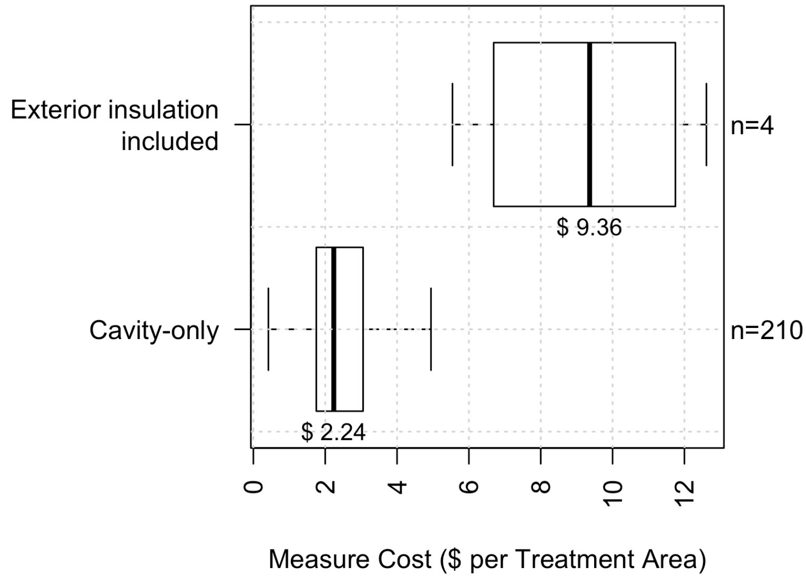


Figure G 60. Wall insulation costs per treatment area for cavity-only vs. exterior insulation projects.

G.10 Foundation

The Foundation section was the 6th most common for recorded measures (exactly tied with Plumbing), with a total of 274 measures, totaling $650,000 of capital investment. Foundation measure total costs are summarized in Figure G 61. The vast majority of foundation measures were insulation, so the insulation measures are summarized by building component in Figure G 62 (see Figure G 63 for cost summaries by treatment area).

The most frequent foundation measures were band joist, framed floor and basement wall insulation. Typical framed floor and basement wall insulation costs were very similar, with median project costs of $1,500-1,600. This remains the case when assessed by treatment area normalized costs, with framed floor insulation median costs of $5.59 vs. $4.95 per ft^2 of insulation for basement walls. These framed floor costs are quite high relative to the normalized costs for attic framed floor ($1.91 per ft^2) and even wall insulation measures ($2.18 per ft^2). There are two primary drivers of the high normalized costs of framed floor insulation. First, as discussed below, this is partly due to frequent use of closed cell spray foam insulation for foundation framed floor, which drives up the median costs. Second, are the high costs of suspending lower-cost fibrous insulation in a framed floor assembly (against gravity), as opposed to the ease of loose fill insulation on an attic floor.

Foundation insulation costs were also determined in the literature review by (Less et al., 2021), and the high-level summary is reproduced below.

- Sealed and insulated crawl: $3.61 - $5.80 per ft^2; total: $5,500
- Basement wall exterior: $3,792 - $7,593 (up to $20,300)
- Basement wall and slab interior: $21,500 - $28,406 (wall-only: $7,000)
- Slab-on-grade perimeter: $16.51 per linear foot

Basement wall insulation projects recorded in the upgrades database were much lower cost (median of $1,544) than these example project costs from the research literature. The treatment area normalized costs in the database were $4.95 per ft^2 for basement wall insulation, which based on the reported total measure costs, suggests that typical basement insulation only addressed roughly 300 ft^2 of area (1,544/4.95). It is possible that only the upper portions of basement walls that are above grade were being insulated in projects in the database, which are the areas with the greatest exposure to exterior conditions and highest rates of heat loss.

Figure G 61. Foundation measure costs.

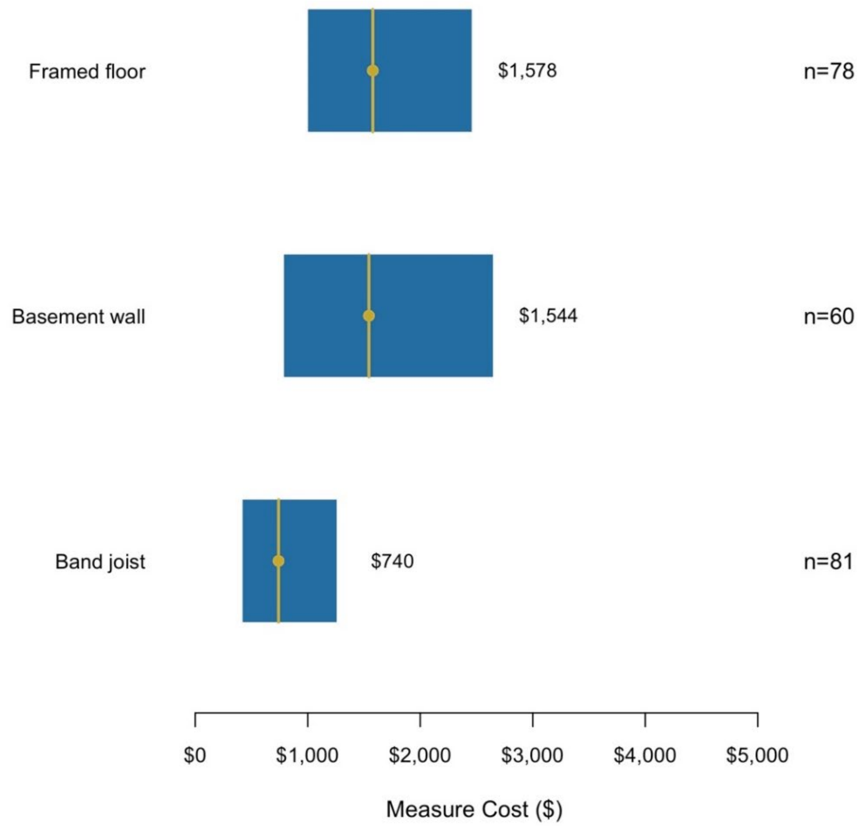


Figure G 62. Foundation insulation costs.

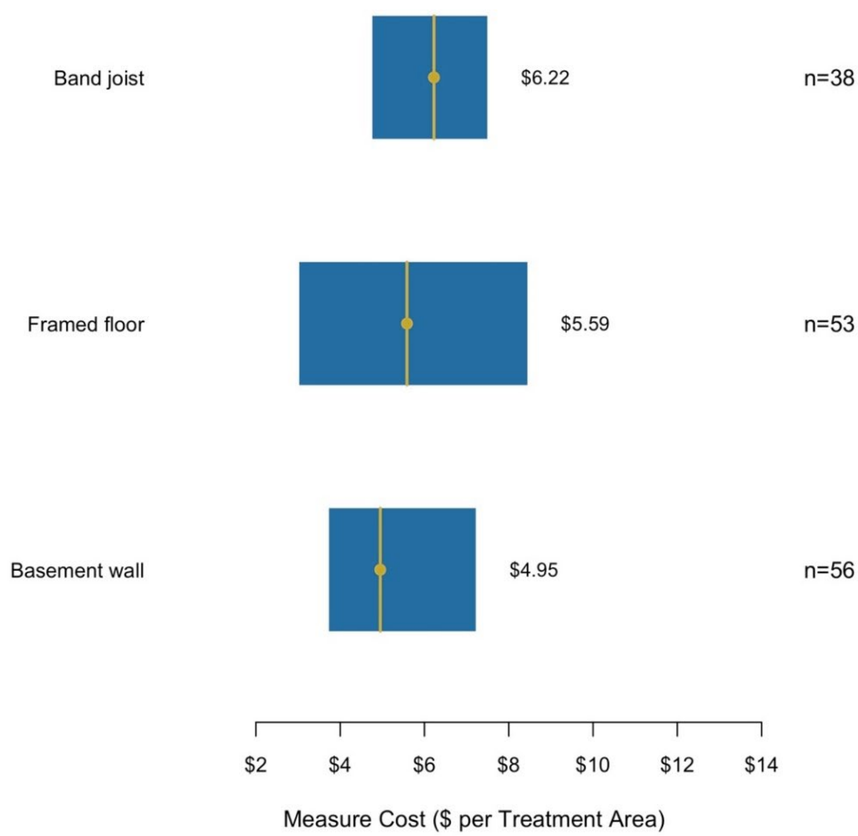


Figure G 63. Foundation insulation costs per treatment area.

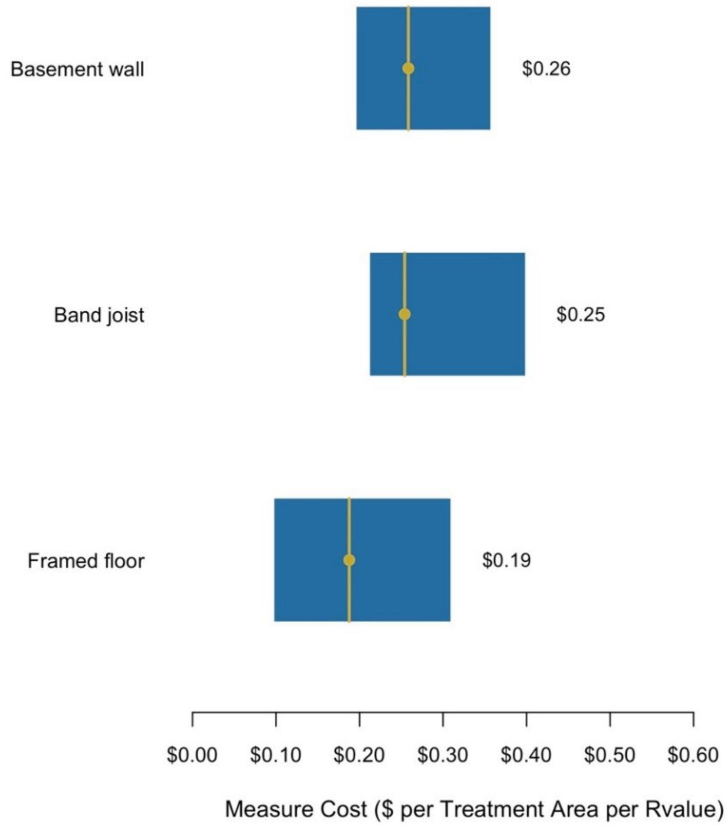


Figure G 64. Foundation insulation costs per treatment area per R-value.

G.10.1 Framed Floor

Framed floor measure total costs are summarized by insulation type in Figure G 65, and the treated surface area normalized costs are summarized in Figure G 66. Across types of insulation, the total project costs are roughly similar (medians from $1,400 to $2,200), with blown cellulose having the lowest costs and closed cell spray foam with the highest. Substantial differences by insulation type emerge when foundation framed floor costs are normalized by treated surface area. In this case, the closed cell spray foam projects had median costs of $8.53 per ft^2, compared with only $3.32 per ft^2 for cellulose insulation. This suggests that closed cell foam projects typically addressed smaller surface areas, such that the total investments were similar. Based on the median cost per ft^2 ($7.64), we suspect that many of the Unknown insulation types were also closed cell spray foam. If all Unknown types were actual closed cell foam, then foam and cellulose were roughly similar in popularity for addressing foundation framed floors. Variable importance for predicting foundation framed floor insulation upgrade costs are shown in Figure G 68, and the most important variables were the treatment area, the dwelling floor area, the project start year, and the type of insulation used.

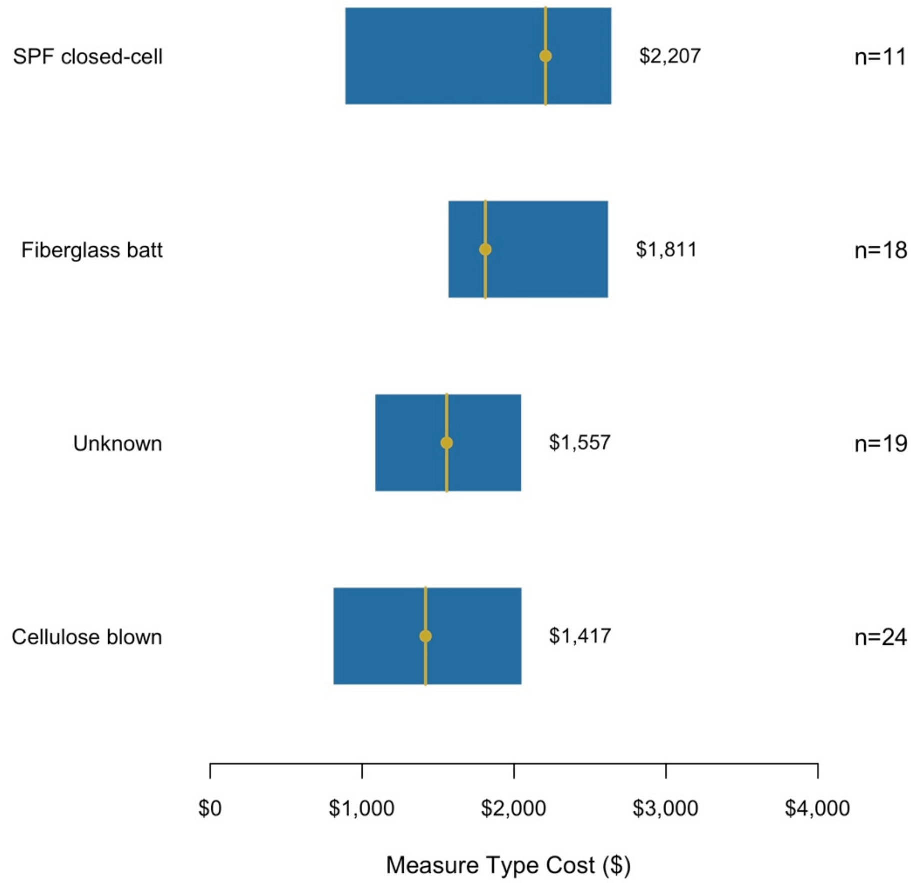


Figure G 65. Foundation framed floor insulation costs.

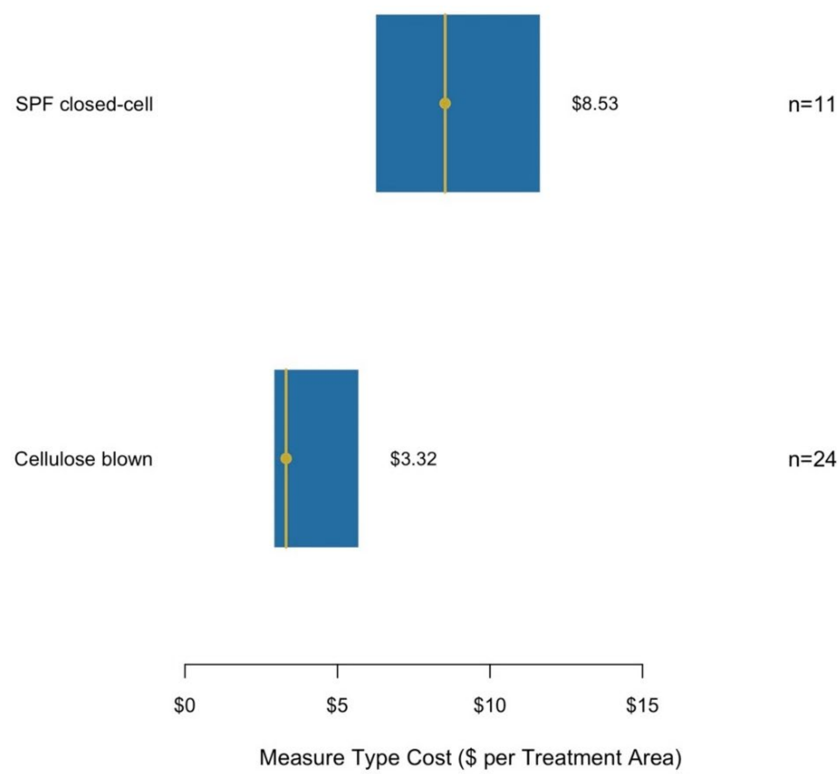


Figure G 66. Foundation framed floor insulation cost per treatment area.

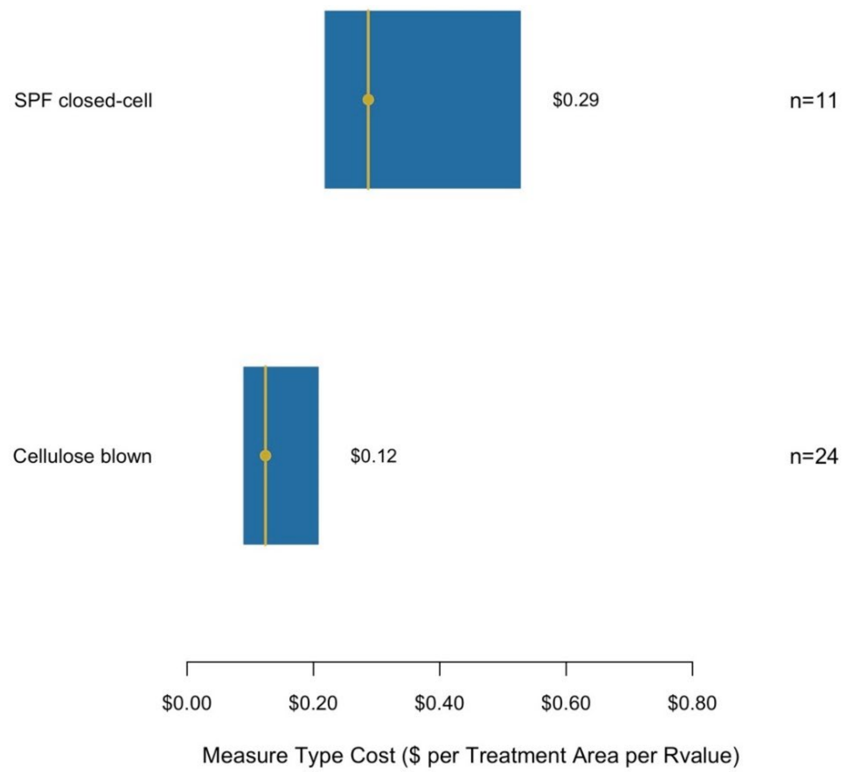


Figure G 67. Foundation framed floor insulation cost per treatment area per R-value.

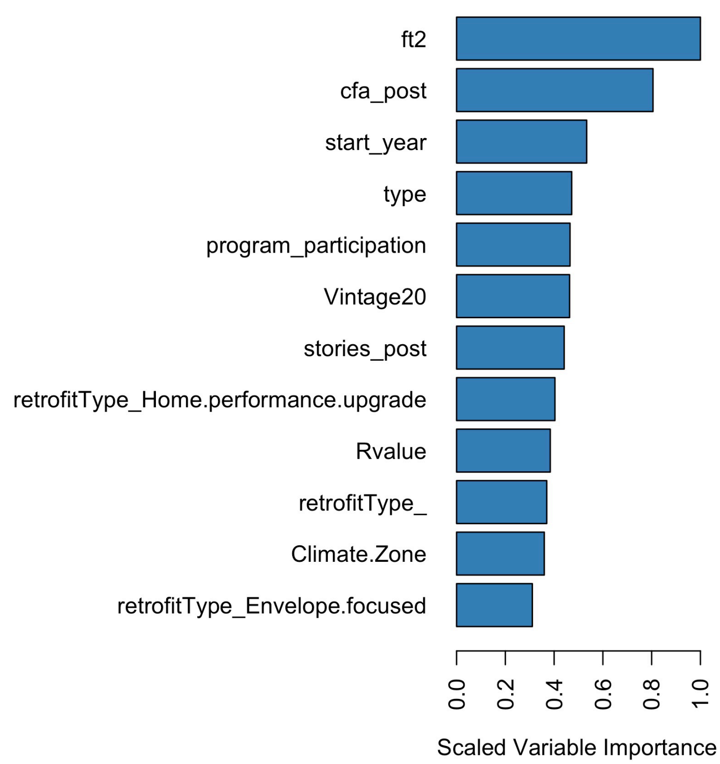


Figure G 68. Foundation framed floor variable importance from random forest regression model.

G.10.2 Basement

Basement wall upgrades were most commonly closed cell spray foam or polyisocyanurate foam board installed on the interior basement wall surfaces. The total and treatment area costs are shown in Figure G 69 and Figure G 70, respectively. The closed cell spray foam costs (\$4.46 per ft^2) were marginally lower than the foam board (\$5.73 per ft^2). Variable importance for predicting basement wall insulation upgrade costs is shown in Figure G 72. The insulation treatment area and the program participation were the most important features in determining measure cost.

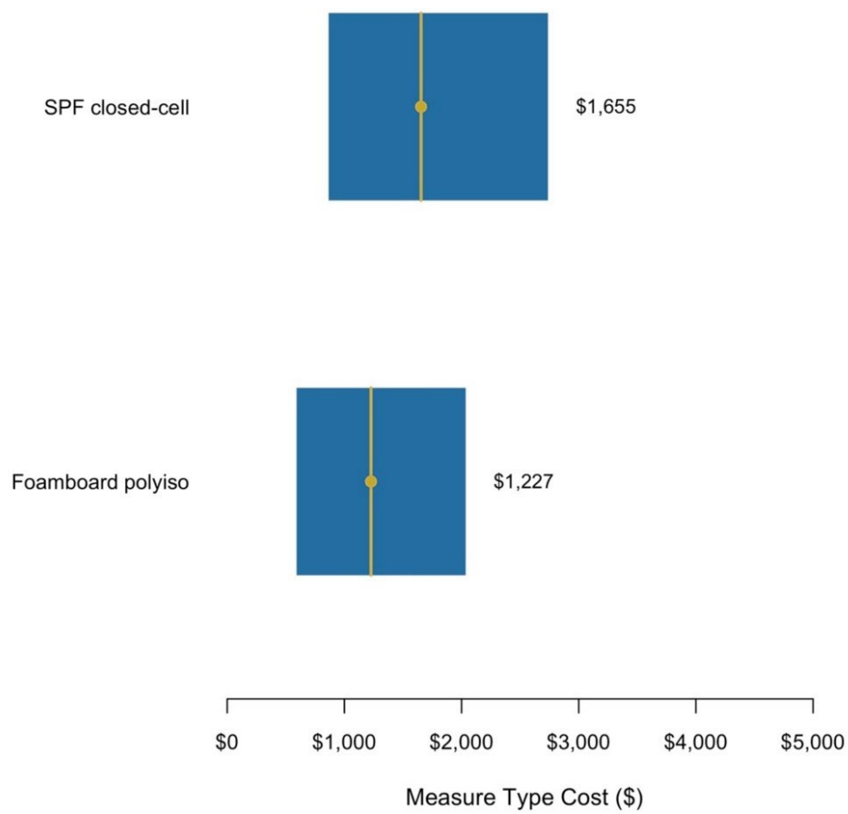


Figure G 69. Basement wall insulation costs.

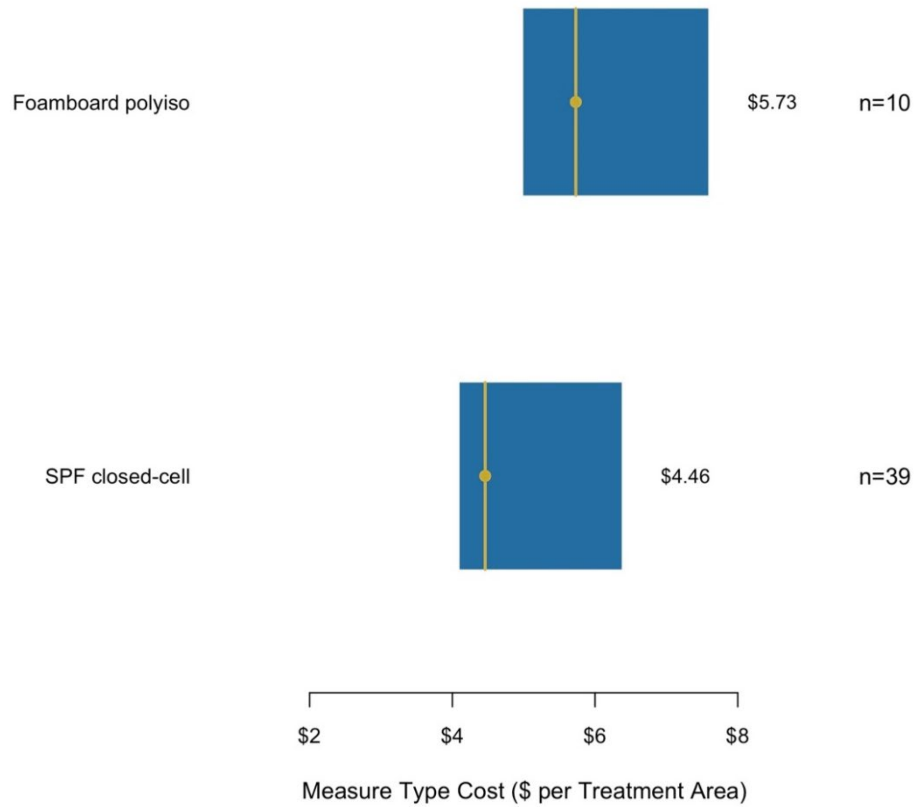


Figure G 70. Basement wall insulation costs per treatment area.

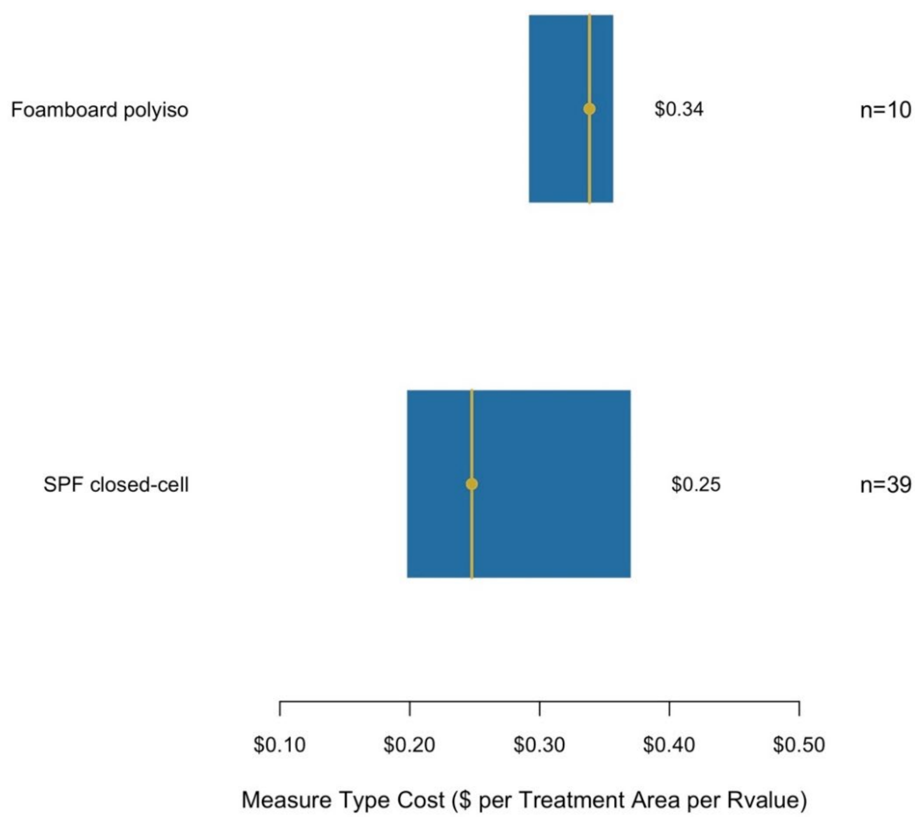


Figure G 71. Basement wall insulation costs per treatment area per R-value.

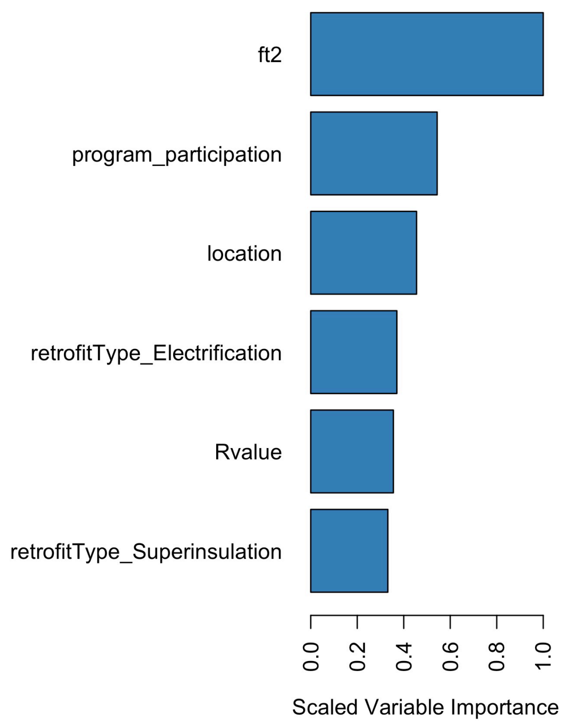


Figure G 72. Basement wall insulation variable importance from random forest regression model.

G.10.3 Band Joist

Band joist areas were most commonly treated using closed cell spray foam insulation at a total project cost of $790 ($6.10 per ft²).

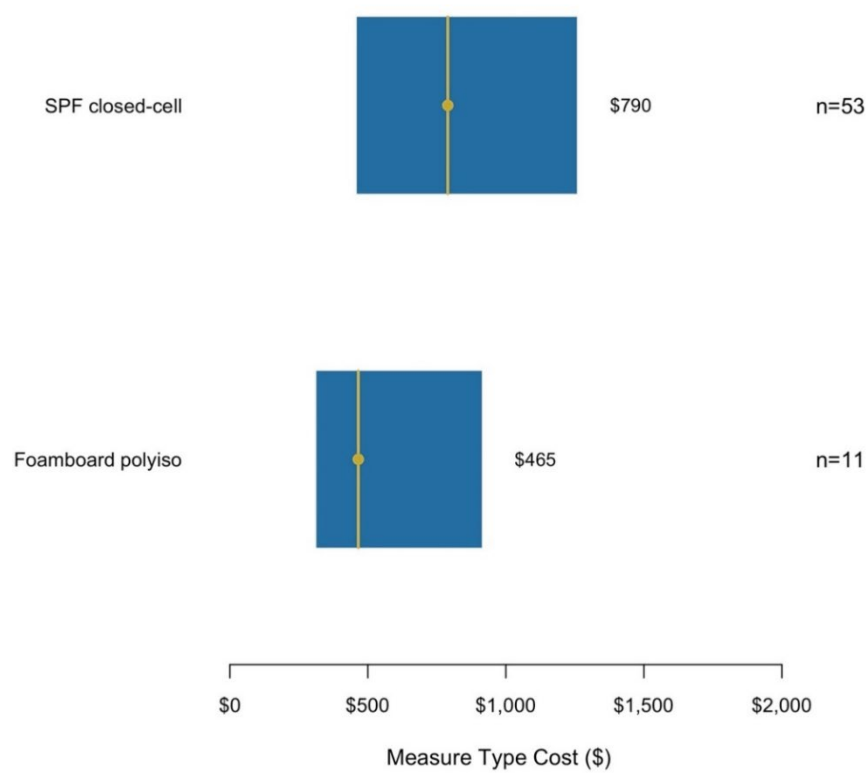


Figure G 73. Band joist insulation costs.

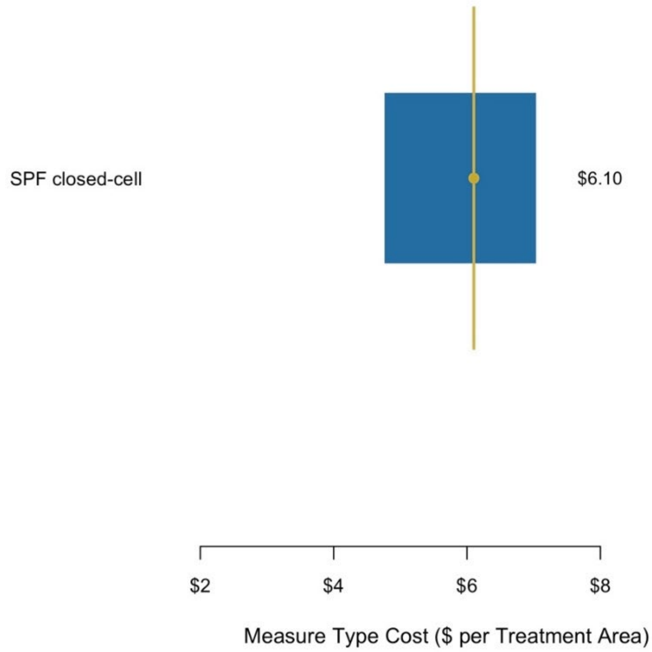


Figure G 74. Band joist insulation cost per treatment area.

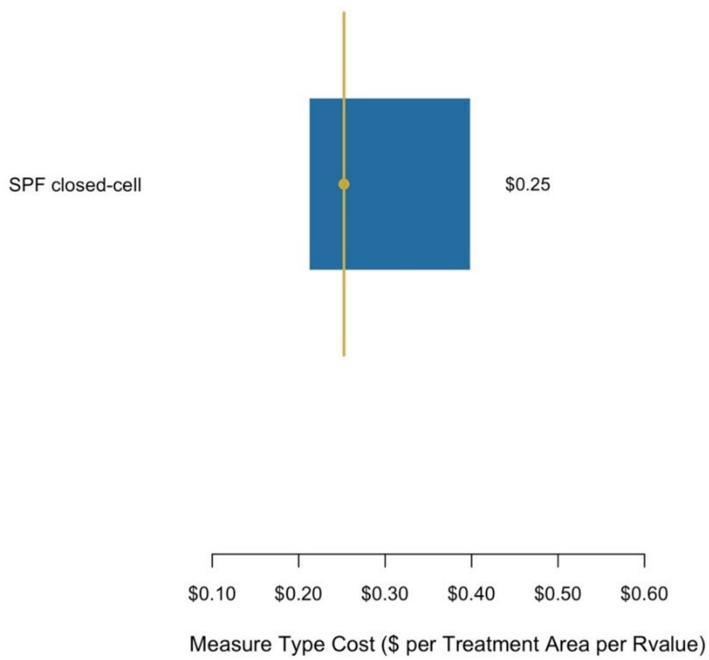


Figure G 75. Band joist insulation cost per treatment area per R-value.

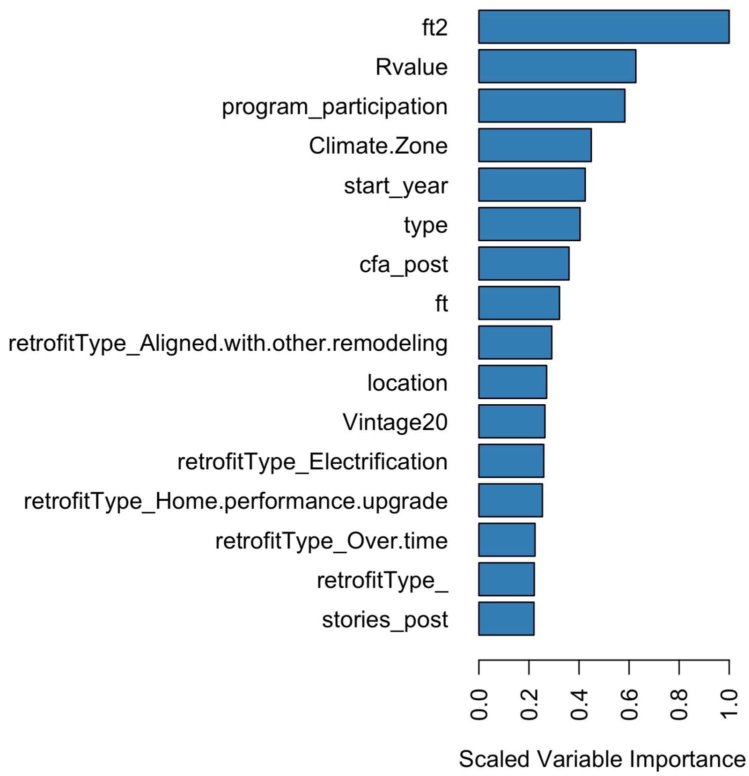


Figure G 76. Foundation band joist insulation variable importance from random forest regression model.

G. 11 Windows and Doors

The Windows and Doors sections were the least frequently addressed in the projects in this database, coming in as the 9th and 10th most frequent Sections. Only 76 window and 42 door costed measures were recorded. Window costs totaled $767,685, while door expenses were $ 62,616. Window costs for each project as summarized in Figure G 77. The unit costs (for each window) are shown in Figure G 78. Window installations typically cost from $3,000 to $12,000 (median $6,500 to $7,500), with a typical cost per window unit of $674. The most important variables in determining window costs were the dwelling floor area, number of stories and window U-value (see Figure G 79).

Most projects did not address the exterior doors. For those costs recorded, they were split between weatherstripping and door replacement. Median door replacement was $1,480, while weatherstripping install was only $99, Figure G 80.

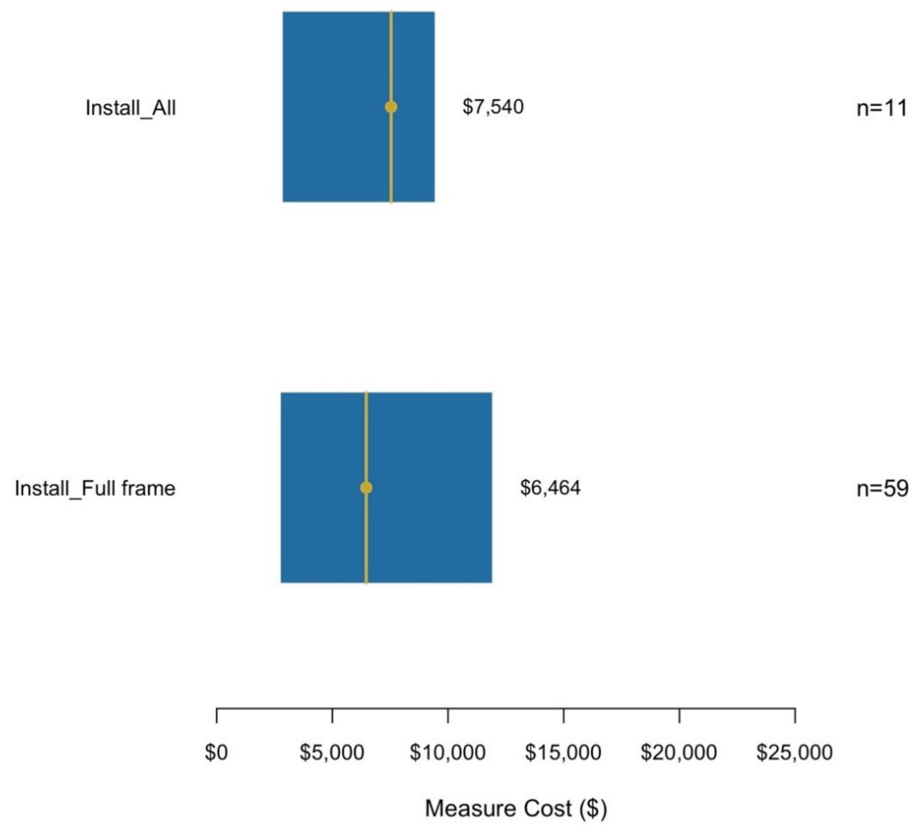


Figure G 77. Window installation costs.

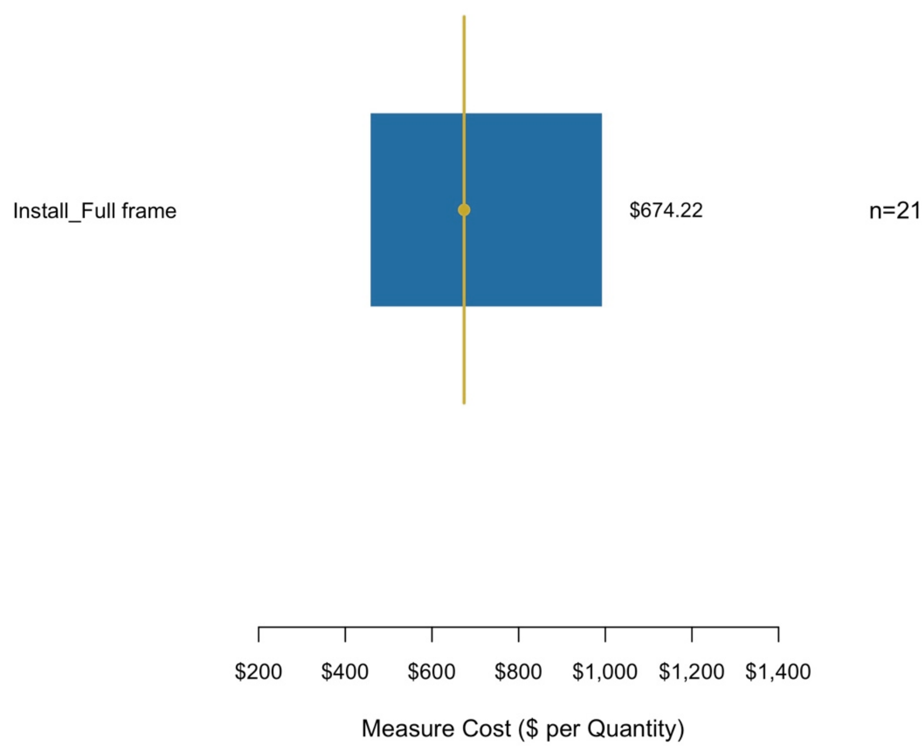


Figure G 78. Window costs per window unit.

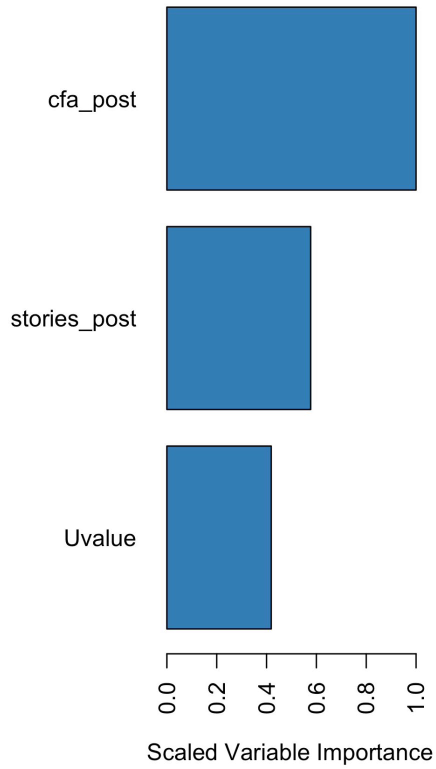


Figure G 79. Window installation variable importance from random forest regression model.

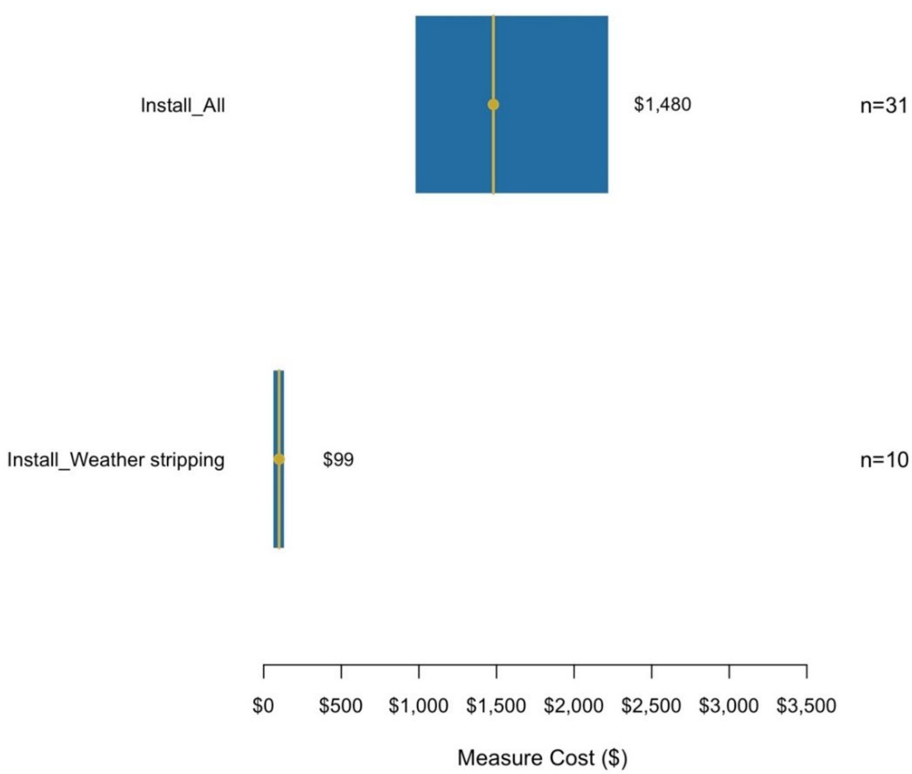


Figure G 80. Door measure costs.

G.12 Plumbing

The Plumbing section was the 6th most frequent (tied with Foundation), with total recorded expenditures of $621,953 and 274 costed measures. The Plumbing measure total costs are summarized in Figure G 81. The Plumbing measures are dominated by water heater installations (n=187; $2,486) and by low-flow fixtures (n=46; $39).

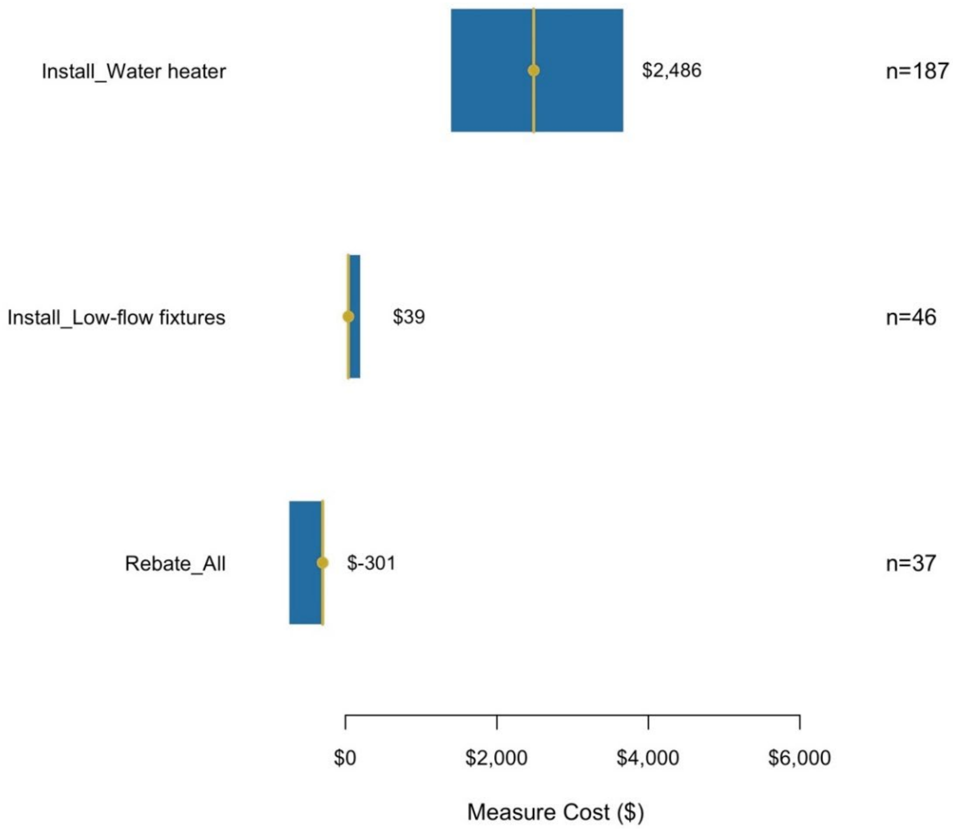


Figure G 81. Plumbing installation costs.

G.12.1 Water Heating

Water heater installation costs are summarized by type in Figure G 82, with further resolution provided by the gallon storage capacity in Figure G 83. Electric heat pump water heaters were the most frequently installed in the dataset, followed by tankless gas and storage electric units. The tankless gas units were by far the most expensive, with median costs of $4,004. The heat pump units were over a thousand dollars lower in cost, at $2,824. Electric heat pump water heater costs varied substantially by tank size (see Figure G 84), with 50-gallon and 80-gallon median installed costs of $2,242 and $3,828, respectively. While not explicitly recorded in the database, we expect that tankless gas costs were so high due to requirements to replumb the typical ½” gas lines up to ¾” for high-output tankless gas heaters. The existing plumbing type was typically unknown, so we do not know how many of the heat pump units were replacing gas vs. resistance electric tanks. Existing electric systems would not require costly electrical upgrades, while replacement of gas equipment typically incurs additional costs. The variables driving water heater installation cost are shown from the random forest regression model in Figure G 85, and the most important factors were water heater type, tank size, energy factor and program participation.

(Less et al., 2021) also summarized heat pump water heater installations costs reported elsewhere in the research literature. The 50-gallon heat pump water heater installations in the SMUD program are much more expensive than typically reported in our database ($3,800 vs. $2,242), while the contractor estimates from (Navigant Consulting, Inc., 2018a) are similar to costs reported for both tank sizes in the database. Navigant estimated the cost breakdown for heat pump water heaters using categories of labor (23-28%), materials (55-66%), supplies (7-12%) and other costs (4-6%).

- Cost curve: $2,263 - $2,714
- Contractor estimates: $2,602 - $4,705
- SMUD +/- 1 Standard Deviation, 50-gallon: $3,000 - $5,000, typically $3,800

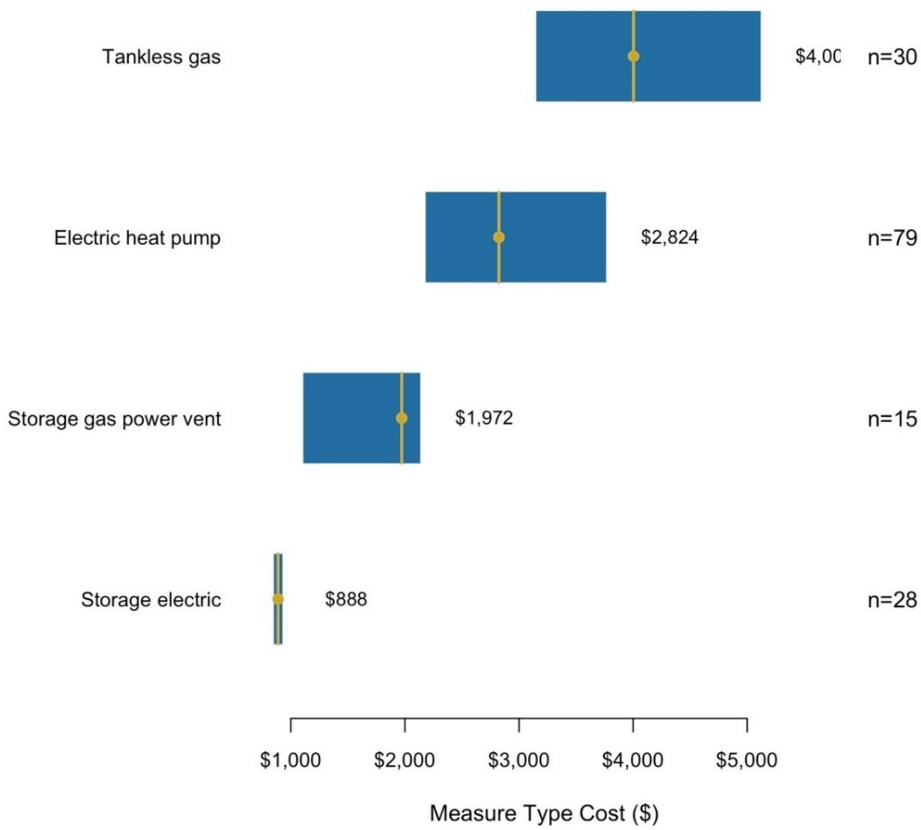


Figure G 82. Water heater installation costs.

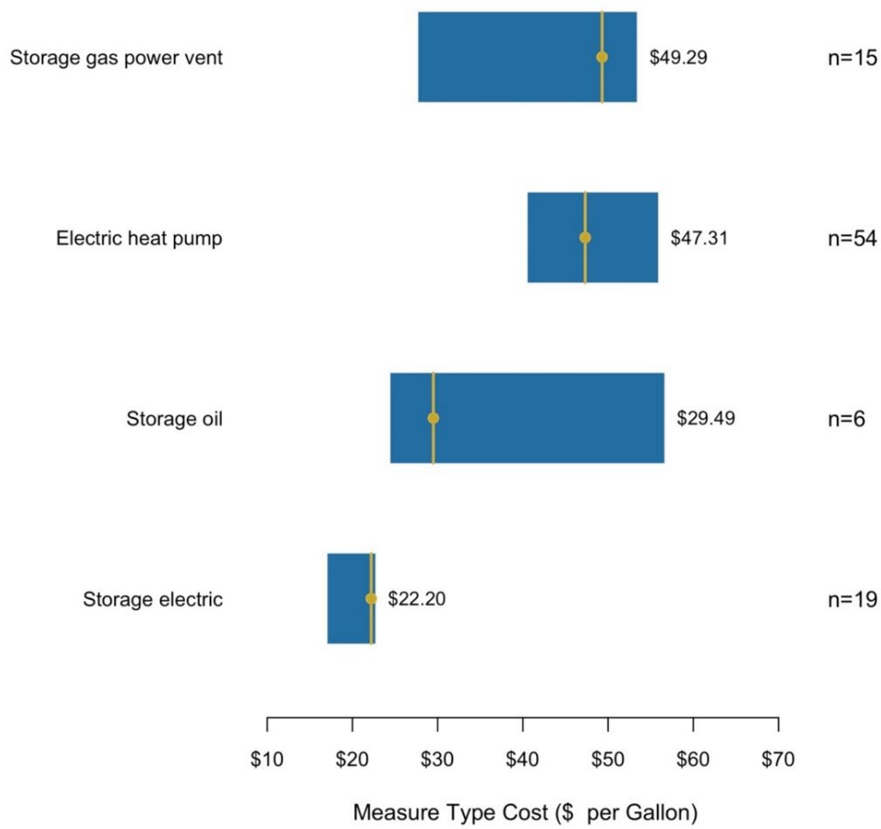


Figure G 83. Water heater installation costs by gallon.

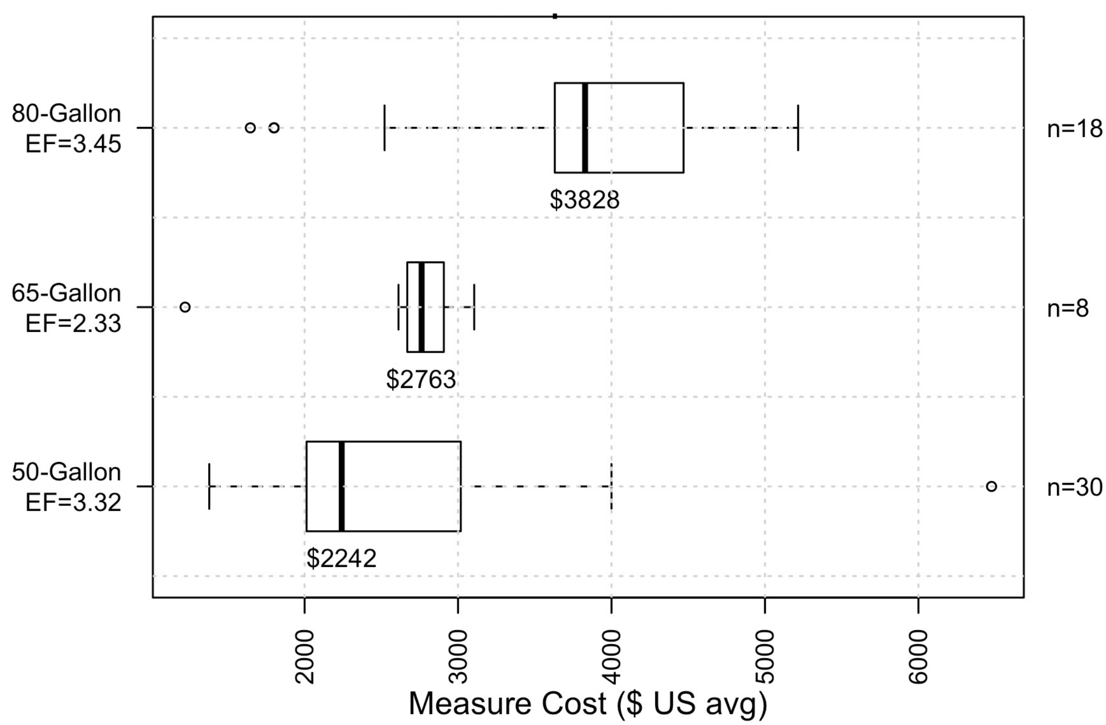


Figure G 84. Heat pump water heater costs by tank size and energy factor.

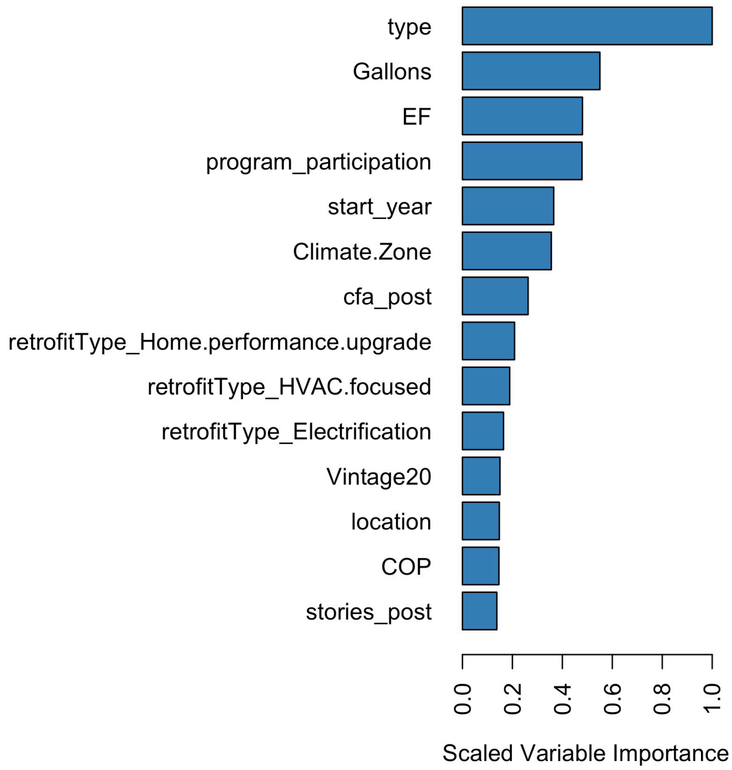


Figure G 85. Water heater installation variable importance from random forest regression model.

G.13 Electrical

The Electrical Section is the 4th most frequently recorded in the database, with 360 costed measures and a total expenditure of $2,445,852. The measure costs for the Electrical section are summarized in Figure G 86. The electrical measures are dominated by PV installation (68) and lighting upgrades (267). Electrical panel service upgrades are common in existing homes with lower total amperage panels (e.g., those 100 Amps or less). The upgrading of electrical service to 200 Amps is of growing importance, as end-uses in homes are converted from gas to electricity, and as other loads require a patch to interface with the grid, including electric car charging and household battery charging technologies. Very few electrical upgrades were explicitly recorded in the database, though we expect that many HVAC and hot water upgrades included electrical expenditures as part of the work scope. Only five "wiring" measures were recorded, ranging from $200 to $800 (median of $679).

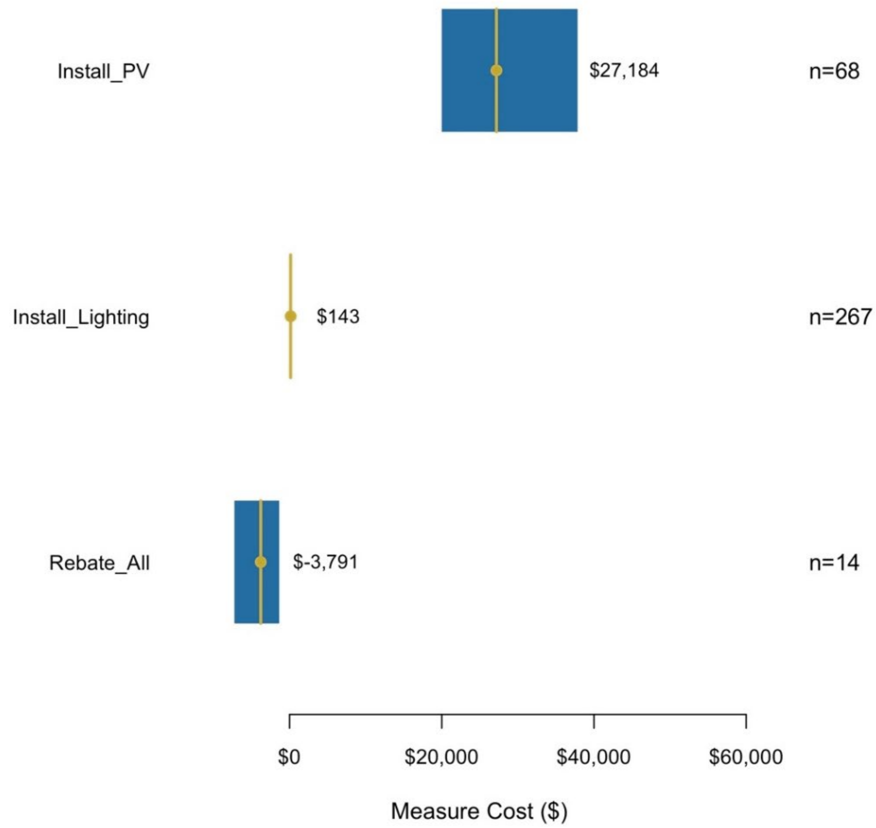


Figure G 86. Electrical section costs.

G.13.1 PV Systems

PV systems were installed in only a small fraction of the projects recorded in the database (68 in total). The median installed capacity was 6.7 kW, varying from roughly 2 up to >15 kW in some instances. The cost of PV installation normalized by the kW has declined over the past 10-years, as illustrated in Figure G 87. The median costs peaked in the year 2011 (outliers excluded) at $6,388 per kW, and these were reduced by more than half to $2,795 per kW in years 2019 and 2020 combined. These reductions are consistent with other efforts to benchmark the cost of solar PV over-time. For example, the NREL residential solar cost benchmark showed peak costs for a 22-panel system in years 2010 and 2011 ($7,530 and $6,620 per kilowatt), with prices dropping down to a range of $2,710 to $2,780 per kW in years 2018-2020 (NREL, 2020). The variable importance extracted from the random forest regression model for predicting solar PV costs ins shown in Figure G 89, and unsurprisingly, the PV wattage completely dominated the installed costs, followed by the dwelling floor area, program participation and climate zone.

The installed capacity of the PV system was also important in determining the system cost. The PV cost normalized by system capacity ($ per kW) is plotted against the system size (kW) in Figure G 88 for installations in 2018-2020. As system size increases, the trend is towards lower normalized costs, such that a small 3.5 kW system is roughly $3,800 per kW, while a larger 12 kW system is roughly $2,750 per kW. The overall cost per kW for these years was $2,795 per kW.

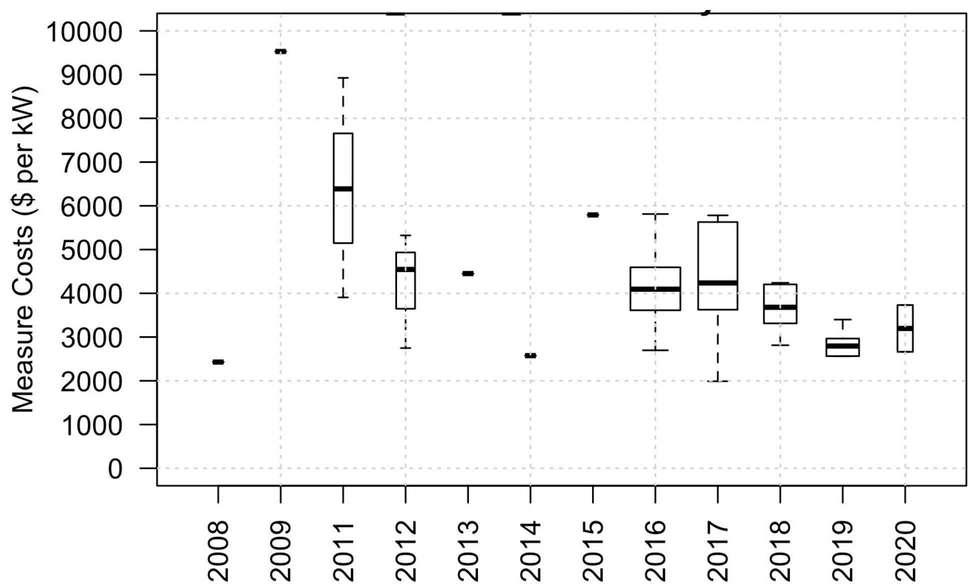


Figure G 87. PV system installation costs, $ per kW.

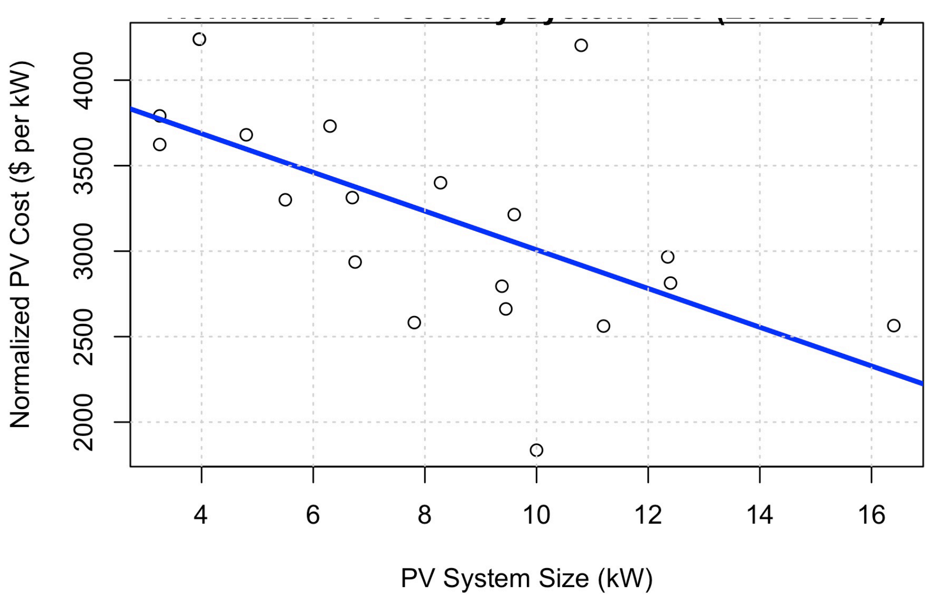


Figure G 88. Normalized PV costs by kW.

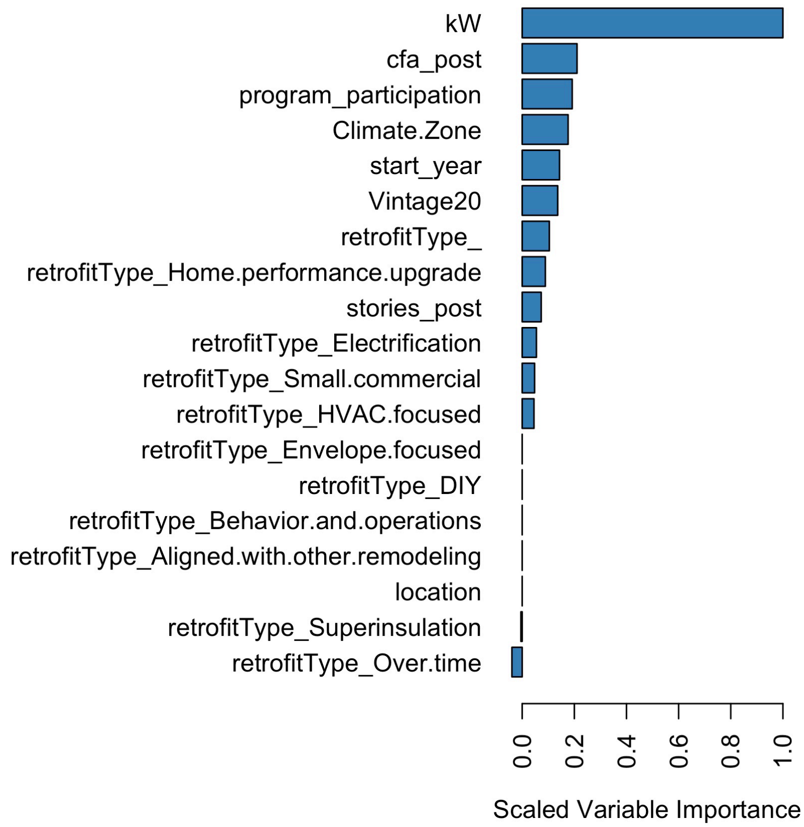


Figure G 89. PV system variable importance from random forest regression model.

G.13.2 Lighting

The measure costs for lighting upgrades by fixture type are shown in Figure G 90, and the costs per unit installed are shown in Figure G 91. As LED bulbs have become commonplace and dramatically lower cost over the past decade, they have replaced compact fluorescent bulbs as the retrofit lamp of choice (194 projects vs. 44 projects using CFL). The LEDs are also lower cost on a per unit basis, at $6.88 vs. $7.81 per fixture. Of those projects that recorded lighting upgrade measures, typically 17 bulbs were replaced at a median cost of $6.875 each. For all lighting measures (including those lacking bulb/fixture counts), the median cost was $143.39. Notably, some projects recorded very large lighting upgrade costs, on the order of $10,000 to $50,000. We do not have specific details on these projects, but we hypothesize that these costs included re-wiring and whole fixture replacement (as opposed to swapping bulbs).

Figure G 90. Lighting installation costs.

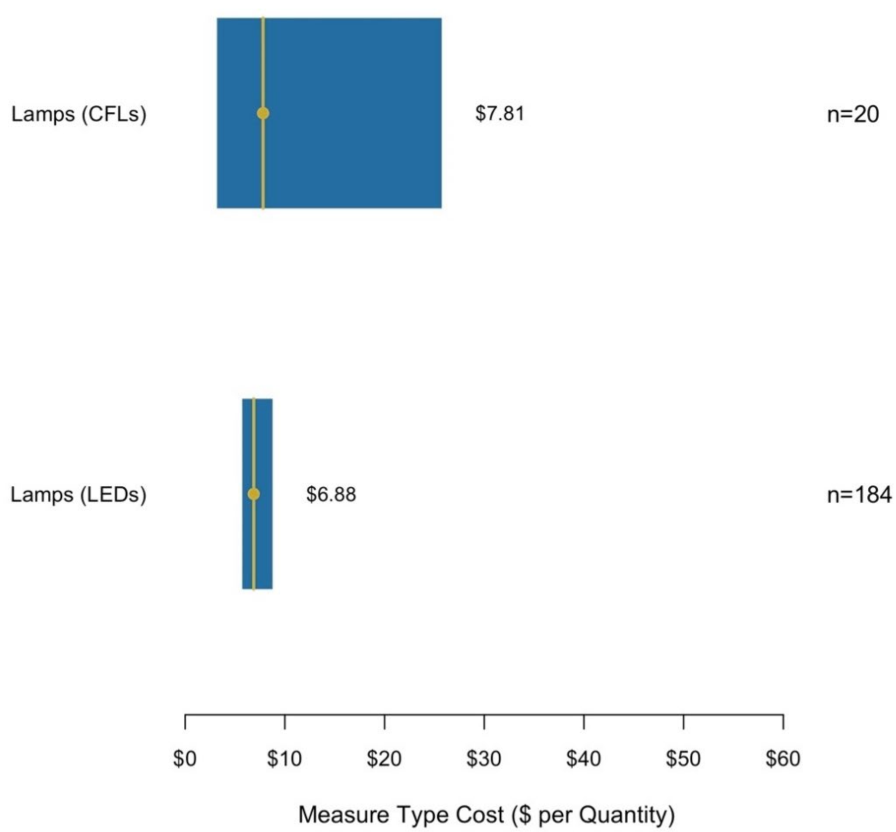


Figure G 91. Lighting costs per unit.

G.14 Appliances

Appliance upgrades were uncommon in the projects contributed to the database. As the 8th most common section, the total expenditures recorded were $122,174 for 100 costed measures. Appliance costs are summarized by appliance type in Figure G 92. Refrigerators were replaced most frequently, followed by dish washers, clothes washers and clothes driers. Notably, no cooking appliance upgrades were recorded in the database, despite the potential health benefits of electrifying cooktop and oven appliances.

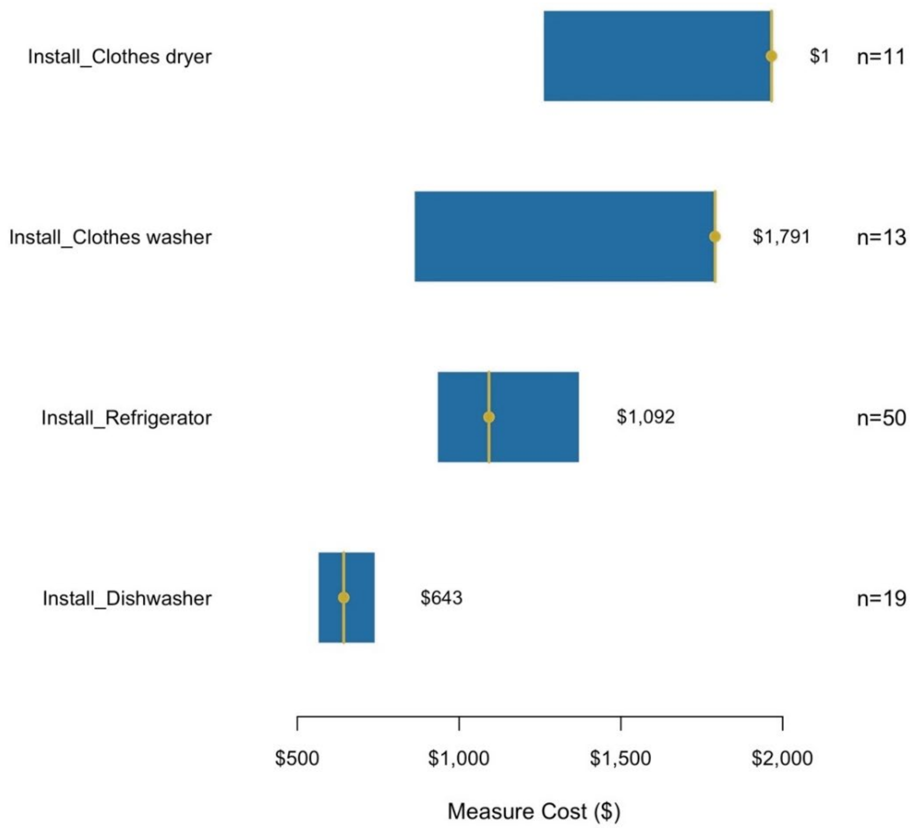


Figure G 92. Appliance installation costs.

G.15 House

The House section, which is a catch-all category, was the 2nd most frequently recorded section in the database, with 1,391 costed measures (not including rebates) totaling $1,974,417. The House section measure costs are summarized in Figure G 93 (see Figure G 94 for floor area normalized costs). The most frequent House measures were whole home air sealing ($729) and general soft costs ($687). Some recorded costs that spanned multiple sections were recorded in the House section (e.g., House_Insulate_All), which leads to some measures in this category having very high costs. These measures reflect roll-ups of costs where no-cost resolution was available at the individual section level.

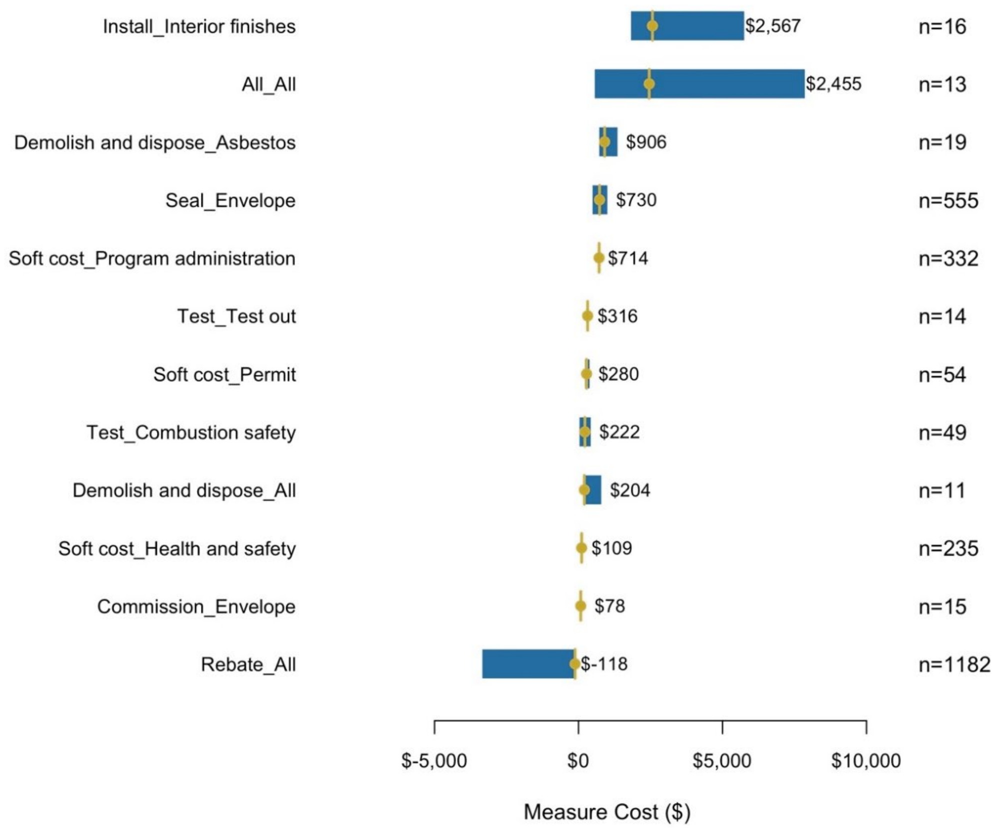


Figure G 93. House measure costs.

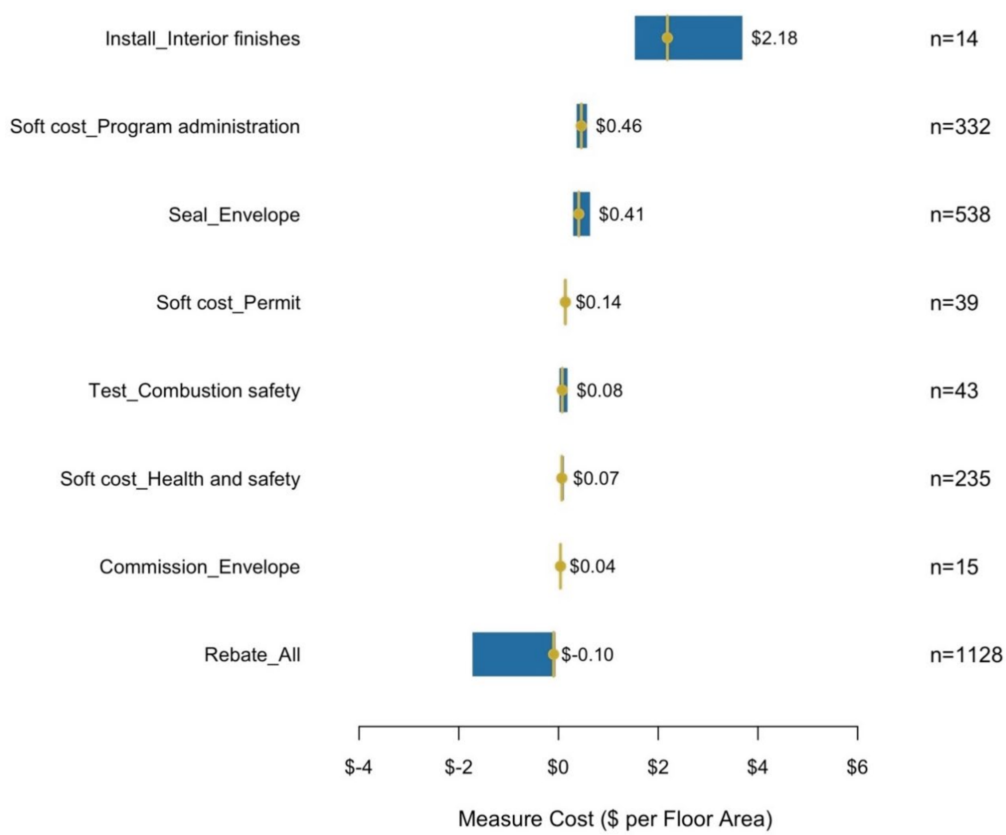


Figure G 94. House measure costs per dwelling floor area.

G.15.1 Envelope Air Sealing

Air sealing of the building envelope was the most frequently reported measure in the House section, with 555 measures at a median cost of $730. Typical envelope leakage reductions were 27%, with some projects achieving upwards of 65% reduction. As shown in Figure G 95, the air sealing costs did increase with increased leakage reductions, but only marginally, from around $600 for <30% reductions to around $900 for reductions >40%. The air sealing costs normalized by conditioned floor area are shown in Figure G 96. These show a somewhat stronger relationship between leakage reduction and cost, but only slightly so. The most important factors in determining air sealing cost (see Figure G 97 for variable importance) were the Program the project participated in, followed by the leakage reduction, the climate zone, and the post-retrofit CFM_{50} value.

It is important to note that the costs of air sealing reported in the database are for direct air seal actions only, and do not include the costs of other measures that might also contribute to leakage reductions (e.g., window replacement, dense pack insulation, etc.).

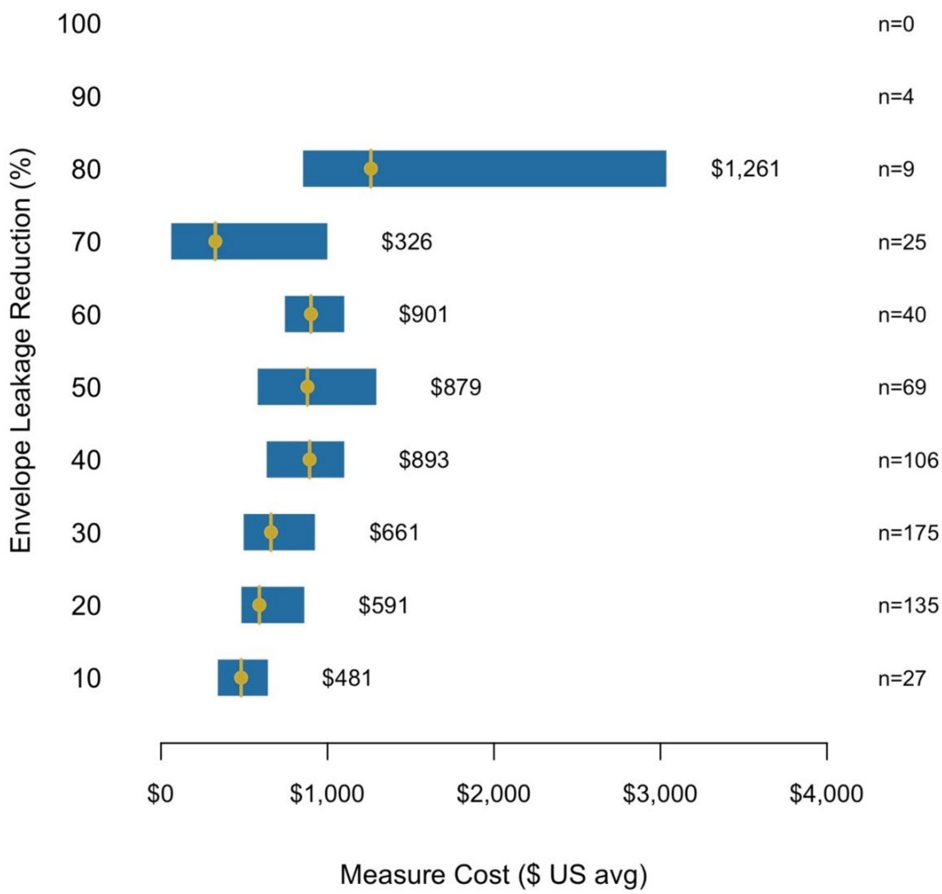


Figure G 95. Envelope leakage reductions and associated air sealing costs.

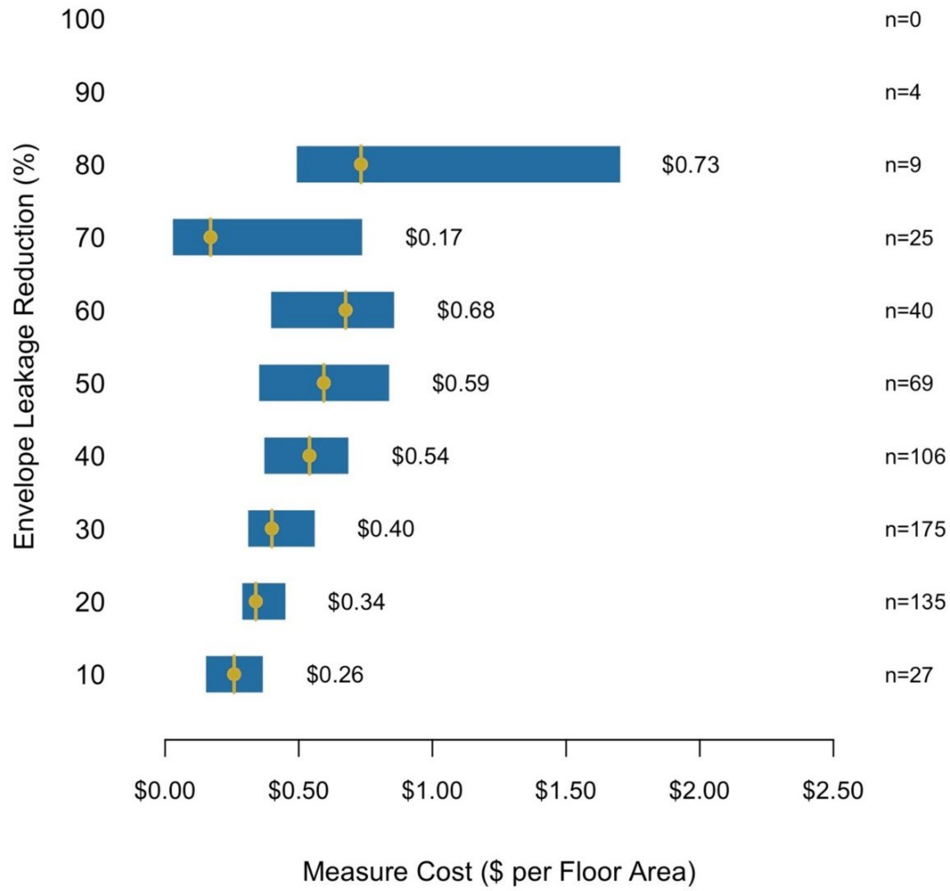


Figure G 96. Envelope leakage reductions and associated air sealing costs normalized by dwelling floor area.

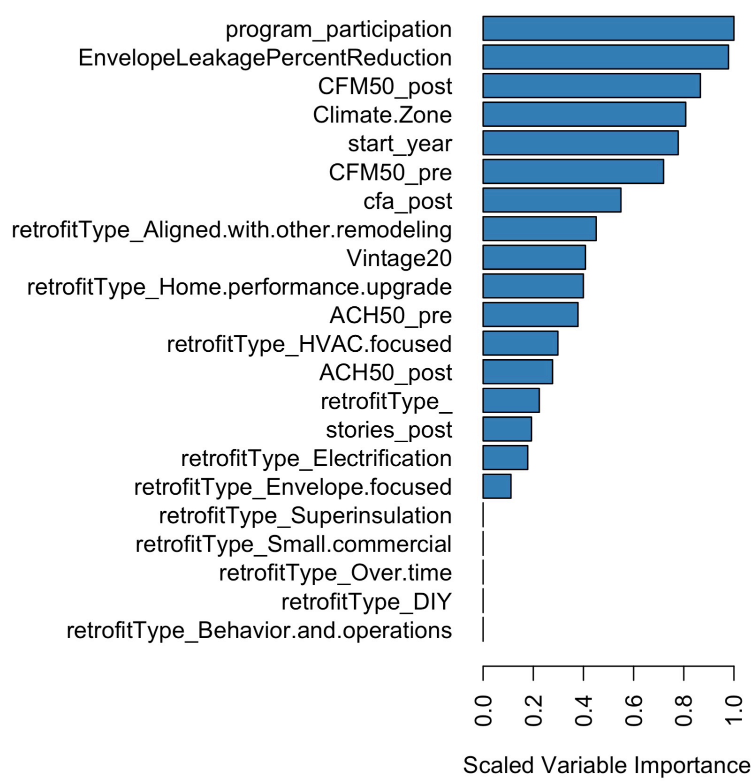


Figure G 97. Envelope air sealing variable importance from random forest regression model.

G.15.2 Soft Costs

Soft costs in home upgrade projects contribute to the project/company overhead costs that along with profit constitute a business's gross margin. Gross margins have been estimated to be 47% of total project costs in home performance upgrade work (Less et al., 2021). Based on a deep retrofit market survey, (Chan et al., 2021) report on typical soft costs in deep retrofit projects, including design costs, customer acquisition, etc. While gross margins are roughly half the total project costs in a deep energy retrofit, there were few soft cost details gathered in the database. These were limited to only program administration, permitting and health & safety work. Of this, program administration costs were the most expensive, at $714 per project. These costs are highly variable by program. Building permits were relatively low-cost, with typical permitting costs of $280, ranging from $100 to $600. Chan et al. reported that permit costs were $1,064 for general building and $264 for mechanical, electrical and plumbing (MEP) permits. Health and safety (H&S) measures are primarily combustion safety testing, with median costs of $109 per project. Chan et al. reported that combustion safety testing costs averaged $387. H&S measures in the database may have been for programs with different testing requirements that were less detailed and time-consuming. While still ensuring occupant safety, reducing such testing requirements is one way to reduce project soft costs.

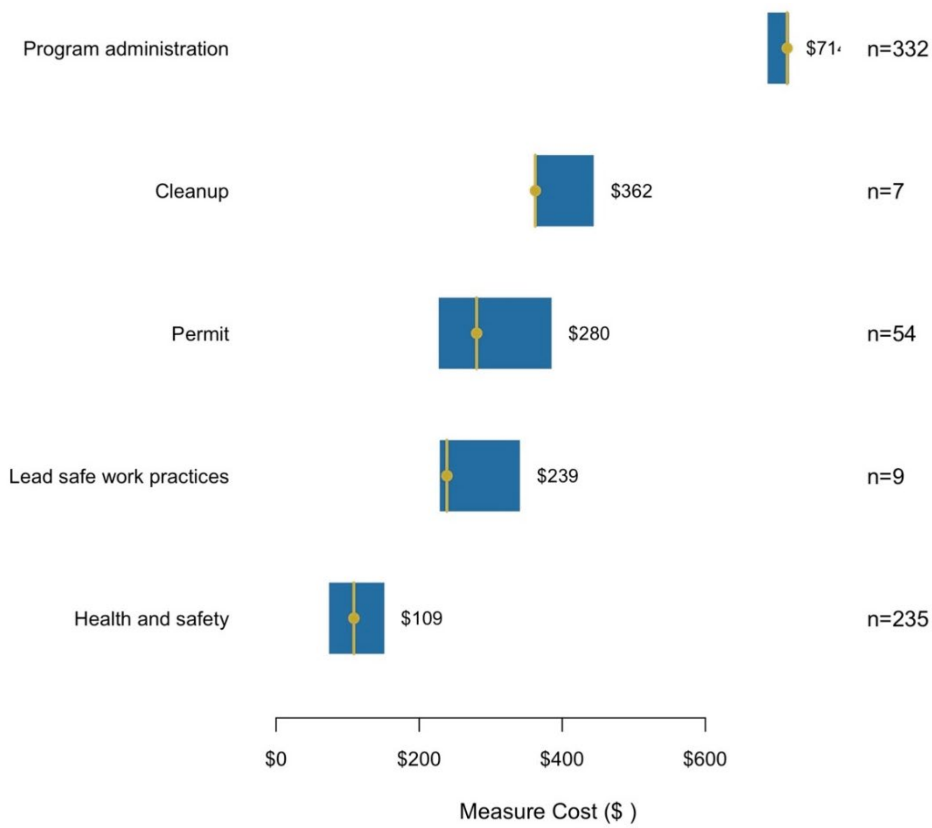


Figure G 98. Soft cost distributions.